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Investigating Perceptual-Cognitive Expertise, Visual Gaze, and Neural Activity in Golf Putting

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Declaration

I hereby declare that the content of this thesis is original and has not been submitted in whole or in part for consideration for any other degree or qualification. I also declare that the thesis embodies the results of my own research.

The PhD was funded by sportscotland from 2014-2019, however, the funders did not have any input into the data analysis, interpretation and writing of the thesis. I declare that the research presented here is issued from my own intellectual work and was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The experiments were designed based on the collaborative work with my supervisors and professional golf coach Steven Rosie. Study 1 was designed in collaboration with my former supervisors, Dr Robin Jackson, Dr Malcolm Fairweather, Dr Joe Causer and Professor Mark Williams. Study 2 was designed in collaboration with Dr Angus Hunter, Dr Malcolm Fairweather and Professor David Donaldson. The remaining studies in this thesis were designed in collaboration with my current supervisory team, Dr Angus Hunter and Professor David Donaldson.

To complete time frequency and power spectral density analysis the EEG data was processed through MATLAB using the open source toolbox of EEGLAB (v13, Delorme & Makeig, 2004). The basis for the pre-processing pipeline and associated scripts were developed by Dr Simon Ladouce and adapted by myself to fit my specific experimental paradigm. To complete MRCP analysis, the EEG data was processed through Brain Vision Analyzer. The basis for the pre-processing pipeline and associated scripts were developed by colleagues at University of Rome "Foro Italico" and adapted by myself to fit my specific experimental paradigm during the time spent in Rome, as part of the Postdoctoral and Early Career Researcher Exchange funded by SINAPSE. Error location data was processed through the open source toolbox of CircStat (Berens, 2009) and associated scripts were adapted by myself to fit my specific analysis.

This thesis adheres to the University of Stirling guidelines for thesis presentation specifying font, font size, 1.5 spacing, margins size (binding edge 35 mm and other margins not less than 20 mm) and mirror margins to allow for doubled-side printing.

"When you change the way you look at things, the things you look at change"

- Max Planck -

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Scientific Dissemination

Part of this work has been communicated as following:

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Invited talks

- Studying golf putting performance – A mobile cognition approach (Conference Symposium, The British Psychological Society, Cognitive Psychology Division, Stirling Scotland, 2020).
- Perceptual- Cognitive Expertise in Golf Putting (Invited speaker, SPARC, Sport and Human Performance Research Group, Sheffield, 2020).
- Investigating the possibility of examining MRCPs in-situ? (Conference Presentation, SINAPSE, St Andrews, and Rome, 2018).
- Investigating the neural mechanisms supporting successful golf putts before and after training intervention (Conference presentation ANT Neuro, Beaune, 2017).
- Part of the Invited Keynote Presentation: Skill acquisition in high performance sport: science to practice insights (BASES Annual Conference, Nottingham, England, 2016).
- Gaze Behaviors of Elite Golfers: Does Task Difficulty Influence Quiet Eye? (Conference presentation in World Scientific Congress of Golf, St Andrews, 2016).
- Is Handicap Rating in Golf an Appropriate Measure of Putting Expertise? (Conference presentation in World Scientific Congress of Golf, St Andrews, 2016).

Abstract

Background/Aims: Perceptual-cognitive expertise, measured through quiet eye (QE) duration has been linked to superior golf putting performance. There are however some unanswered questions in relation to how QE duration improves performance and inconsistencies when trying to apply optimal QE duration in practice. Consequently, the overarching aim of this thesis was to identify factors of perceptual-cognitive expertise related to golf putting performance.

Methods: To explore the impact of QE duration on performance, Study 1, Study 2 (a, b, c) assessed gaze behaviour, performance, stroke kinematics and neural activity. The final studies explored perceptual-cognitive expertise in golf putting through exploring the whole putting routine capturing gaze behaviour, performance and stroke kinematics alongside golfers and coach ratings. A mixed method triangulation design was used to interpret the data and to develop further understanding of perceptual-cognitive expertise in golf putting.

Results: Shorter QE durations were most effective for performance, influencing our decision to explore perceptual-cognitive expertise beyond QE. Exploring the interaction between the golfer, task and environment formed the basis of the development of an intervention designed to improve performance. Observable neural signatures differentiating successful and unsuccessful putts were also found. Furthermore, we found even within a highly skilled cohort a high level of within and between variation in performance, gaze and kinematic measures.

Conclusions: Findings reveal perceptual-cognitive expertise in golf putting is multi-faceted and goes beyond QE duration. We discuss the benefits of future research adopting an Ecological Dynamics approach to explore the complex interactions between the task, individual and environment. The challenge lies in collecting combined synchronised EEG and eye tracking data and we suggest future studies employ longitudinal designs to examine changes in expertise over time. It is proposed any applied recommendations are devised on an individual level.

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Thesis Outline

The advancement of mobile research methodologies has provided the ability to gain insights into gaze strategies, neural activity and stroke kinematics adopted by expert athletes. Each measure has generated a lot of interest and as a result there are already interventions designed to improve sporting performance through re-training gaze strategies, engaging with neurofeedback/"brain training" or to improve technique by altering stroke kinematics. The efficacy of these interventions, including the well-documented visual strategy of 'quiet eye (QE)' as a specific factor influencing performance has been questioned (Baker & Wattie, 2016). Consistent with this, researchers trying to apply QE duration with elite athletes found optimal QE duration does not always lead to successful performance (Farrow & Panchuk, 2016). The problems associated with translating findings from research to practice may be in part due to when studying the relationship between QE duration and performance there has been limited studies conducted using a representative task design with elite golfers. The concept of 'representative task design' (Brunswik, 1956), refers to the arrangement of conditions in an experiment so they represent the behavioural setting, to which the results are intended to apply. Representative task designs enable the researchers to explore the psychological processes that underpin perceptual-cognitive expertise *in situ* as the perceptual environment that informs action has been appropriately recreated (Stone et al., 2015). Consequently, the focus on the first study within this thesis (Chapter 3) was to observe behaviour and QE duration in high skilled golfers to examine the impact of QE duration on performance when using a representative task design. The use of a representative task design also enabled us to explore how QE duration varies as a function of task difficulty.

Our findings from Study 1 (Chapter 3) revealed shorter QE durations were most effective for performance. Additionally, we unexpectedly found considerable variation within and between participants for performance, QE durations and kinematics. These findings are not consistent with the location suppression hypothesis (most cited explanation for why a longer QE duration is beneficial for performance), therefore added to the call for further research into understanding QE and its functional mechanisms related to performance (Causer et al., 2010). The focus of Study 2, which consists of three parts (Chapters 4, 5 and 6), was therefore to complete the pending *"empirical tests on the hypothesis of an optimal QE period"* (Klostermann et al., 2014,

p. 2176). QE intervention training has been recommended for teaching optimal QE durations in golf putting (Vine et al., 2011). The performance gains conferred from QE intervention training are reported to be ‘perhaps the most exciting finding’ from an applied perspective (Wilson et al., 2016, p1). In Study 1 (Chapter 3), QE durations recorded were typically shorter than the recommended optimal QE duration time, although differences in the QE definition used make a direct comparison challenging. Consequently, we were keen to explore whether you need to be trained in a QE intervention to experience the performance benefits associated with a longer QE duration. Study 2a (Chapter 4), was designed to employ a within participant design to examine what impact optimal QE duration (informed by QE intervention training) had on performance in golf putting. QE intervention training did improve performance in comparison to the control, however, the performance benefits were less clear when analysing the data on a trial-by-trial basis and there were some concerns over the impact of practice on performance given the study design.

In Study 2b (Chapter 5), we wanted to complete further investigation with the addition of mobile EEG to improve understanding towards the potential mechanisms underpinning QE (Gonzalez et al., 2017; Williams, 2016). We also wanted to explore whether neural activity was related to performance to gain further understanding of perceptual-cognitive expertise. We found that neural activity could be used to differentiate between successful and unsuccessful putts with specific observable neural signatures, offering promise for future research. More specifically, superior putting was associated with enhanced preparation. There were, however, individual differences within the findings and methodological limitations related to trial numbers (Study 2b and Study 4), the choice of trigger and head/eye movements inherent within golf putting. Moving forwards, we recommend implementing longitudinal research over multiple sessions to address these limitations.

In Study 2c (Chapter 6), we completed a follow up study, to address concerns of the design of the Study 2a (Chapter 4). Critically our findings revealed a QE intervention did not improve performance once practice had been accounted for, subsequently questioning the efficacy of QE intervention training and the recommendation that a longer QE duration is beneficial for performance. The design of QE training interventions and associated research methods in literature has been underdeveloped (Renshaw et al., 2019). The series of studies in Study 2 (a, b, c) were designed to extend the current evidence base by exploring the function of a longer QE duration over multiple studies and sessions. In this series of studies, we also wanted to address any potential concerns from Study 1 (Chapter 3) regarding the lack of control in the representative study design (Stone et al., 2014; Stone et al., 2015) and definition of QE duration used (Walters-Symons et al., 2018). The collective findings from Study 2, suggest that longer QE duration should not be used as a reliable marker to differentiate performance. These findings led us to widen the scope of this thesis beyond QE to explore additional aspects of perceptual-cognitive expertise in golf putting. The remaining studies therefore focused on exploring perceptual-cognitive expertise beyond QE duration in relation to performance.

Study 3 (Chapters 7 and 8) consisted of two parts; i) Study 3a: a screen-based task with 2D images and videos (typical of cognitive approach to studying perceptual-cognitive expertise, for more details see Table 1 and Chapter 2) and ii) Study 3b: a behavioural experiment (conducted in summer and winter) which was representative of an Ecological Dynamics approach (for more details see Table 1 and Chapter 2). To explore the reciprocal relationship between athletes and environment, from a perceptual standpoint (Gibson, 1979), including understanding the demands the environment places on an athlete's existing action capabilities (Dicks et al., 2009; Gibson, 2015). Study 3 aimed to explore more broadly what sources of information golfers use when putting, and how golfers use this information to inform their actions (present and future), especially when reading the green and evaluating their putt. Findings revealed green reading does impact performance and golfers (even those who are highly skilled) do not always accurately read the green, set up to their putt, and/or evaluate their putt. The study provided insight into the processes underpinning putting success and was used to form the basis of the perceptual-cognitive intervention designed in the final study.

The final study in this thesis (Study 4, Chapter 9), was designed to explore if a perceptual-cognitive intervention could improve performance in highly skilled golfers. Findings revealed the perceptual-cognitive intervention did improve putting performance and the golfer's ability to accurately evaluate their read, aim point, pace and execution. However, these findings are limited due to the short intervention, limited time between pre and post-tests and lack of retention or transfer tests so any performance benefits are tentative at best until further studies with these controls are in place. To further develop understanding into perceptual-cognitive expertise, the challenge still lies in collecting ‘clean’ EEG data *in-situ* and combining synchronised EEG and eye tracking data.

In summary, this thesis highlighted the importance of understanding and exploring individual differences, even within a highly skilled cohort. The findings illustrate the importance of matching the research task to the applied competitive environment to accurately disseminate key learnings to golfers, coaches, and sport practitioners. Taken together, the findings of this thesis offer a novel way of exploring and understanding perceptual-cognitive expertise in golf putting.

Chapter 1: Introduction

The aim of this thesis is to understand the psychological processes that underpin perceptual-cognitive expertise, in the context of elite golf putting. Putting is a key element of golf, whereby a putter is used to strike the ball towards the hole, when the ball lies on or just short of the area known as the green. Understanding how putting expertise is developed is critical, as it has been reported that putting accounts for 41% of shots per round (PGA Tour, 2015), making putting performance one of the key factors determining earnings (Alexander & Kern, 2005; Hellstrom, 2009).

To explore the psychological processes, this thesis employs methods from cognitive neuroscience (including measures of behaviour, eye movements and brain activity) to examine correlates of successful sporting performance. The use of eye-tracking to assess visual strategies employed during performance has provided insights into the cognitive processing through tracking what athletes pay attention to and how this visual information guides their actions (Moran et al., 2018; Panchuk et al., 2014). Mobile Electroencephalogram (EEG) is a physiological technique which measures brain wave activity in real time without modifying the behaviour (Kranczioch et al., 2014; Ojeda et al., 2014). Measuring brain activity offers a potential way to understand neural mechanisms associated with expert performance (Park, Fairweather, Donaldson, 2015). Additionally kinematic measures to assess the motor control of the putting stroke will be captured as a marker of putting expertise (Bienkiewicz et al., 2019; Grealy & Mathers, 2014). One of the overarching aims of this thesis is to capture data from a range of measures to explore if markers of optimal performance differ from those of unsuccessful performances (Filho et al. 2015) either within the same individual (Ruiz et al., 2017), within a cohort of elite golfers and across a range of expertise.

To date, research exploring perceptual-cognitive expertise in golf putting has focused almost *exclusively* (Lebeau et al., 2016; Mann et al., 2007) on the quiet eye (QE) defined as the final fixation or tracking gaze at a task-relevant location prior to the initiation of the final phase of the movement (Vickers, 2007). QE is proposed to be one of the key determining factors of golf putting success (Vickers, 2007) and research has shown highly skilled golfers who are trained in QE intervention perform better than those who are not (Vine et al., 2011). These findings are supported by Lebeau *et al.* (2016) meta-analysis, which found a moderate effect size comparing QE periods for successful and unsuccessful performances within individuals. Research has had a prolonged interest in QE with studies spanning over 25 years and 581 published papers on QE (as reported in Rienhoff's et al. 2016 meta-analysis). Despite this attention on QE, the underpinning mechanisms are still not known (Gonzalez et al. 2017). Consequently, this has often led to practitioners applying QE without knowing why it works (Williams, 2016), and at times this approach has produced inconsistent results (Farrow & Panchuk, 2016). These findings are concerning given the context of this thesis. This thesis was funded by a National Sports Organisation who wanted to gain knowledge on performance improvements in this area. In this case any recommended strategies for practice must be supported and explained by evidence and if requiring a change from typical behaviour then critically more effective than current practice (Bishop, 2008). In accordance with this approach, the studies in this thesis were not designed from the sole perspective of one theoretical orientation. It is acknowledged that this approach is not without limits, particularly as methodological designs may be more variable and contain greater error than under controlled conditions (Bishop, 2008). However, the overall aim is to create successful transfer from research to practice and in the given context, recommend practice that we can explain how and why it works or crucially why current recommendations are producing inconsistent results. Varying the methods does allow us to be open to explore/test alternative theoretical perspectives within the thesis (Table 1), and these findings will support the secondary aim of guiding understanding towards what theoretical perspective is best suited to explore perceptual-cognitive expertise in golf putting in the future.

There is also a wider issue related to the dominance of QE duration as the majority of studies have been conducted in a testing environment that has not needed to recreate the perceptual environment of applied competitive putting (Renshaw et al., 2019). We recognise that QE duration has roots in cognitive psychology (Rienhoff et al., 2016) and this has influenced current research design with the predominant task employed being a repetitive task with the same putt taken from one place. Consequently, other areas/markers of perceptual-cognitive expertise in golf putting have been under explored. More specifically, in applied competitive golf putting, there are several distinct phases: 1) the pre-motor evaluation phase, 2) the motor phase, and 3) the post-motor phase. In the pre-motor phase, the golfer considers the putting green environment, by exploring and assessing relevant topology in relation to the putting problem that needs to be solved (e.g., what direction and strength of shot will get the ball into the hole). This phase of the putting routine includes an interactive evaluation of the environment, the present initial conditions and the solution of choice. Despite these critical factors there is very limited research on this phase (Carey et al., 2017) and as a result, there is limited understanding of how a golfer develops skillful perception.

The motor phase is concerned with the pre-shot routine, including motor preparation and shot execution. During this phase, the golfer's feet are static and located alongside the ball, as they prepare to initiate putter club movement and strike the ball towards the target. The putting action can be broken down into four phases: backswing, downswing, impact, and follow through (Burchfield & Venkatesan, 2010). The optimal temporal ratio of the backswing to the downswing is 2:1 (i.e., the backswing phase is twice as long as the downswing; see (Grober, 2009; Kooyman et al., 2013) regardless of the target distance of the putt (Grober, 2011). The majority of research investigating putting has examined this stage, with a significant focus on the importance of Quiet Eye (QE, Vickers, 2007) which emphasizes the importance of focusing attention on the final fixation on the back of the ball.

The final post-motor stage occurs after the ball has been hit and from a cognitive perceptual point of view, there is limited research on this stage beyond QE Dwell (Vickers, 2007). QE Dwell signifies where the eyes are looking in the post putt period. QE Dwell research proposes the golfer should look at the ground where the ball was, just prior to contact for up to 300ms post contact. Vickers (2007) believes encouraging golfers to maintain focus for an extended period after hitting the ball can help enhance quality of stroke. Whilst QE Dwell has attracted considerable attention within golf putting research, the behaviour of a golfer keeping their head still after shot is not observed in Tour Players. Elite level golfers are typically observed to track the ball from the moment of contact, potentially increasing the type of perceptual feedback the golfer could receive; feedback that would be limited if the golfer kept their head still post contact. Further research is required in this area to explore how QE Dwell influences putting in the context of expert performance and this will be examined within the data chapters in this thesis.

At this stage little is known about the broader aspects of how the golfer interacts with the environment and develops perceptual expertise across the whole putt routine.

Research informed by an Ecological Dynamics approach may be able to offer an alternative approach to understand perceptual expertise (Davids & Araújo, 2016). An Ecological Dynamics approach postulates an individuals' movement responses are shaped as a result of the continuous dynamic interaction between the individual, task and environment (Araújo et al., 2006). Gibson (2015) describes how the brain and body (sub)systems are involved in an active process whereby the perceptual and action systems function in a highly integrated, interconnected and cyclical manner. Using this approach gaze measures such as QE, would be considered not on the basis of information processing terms (e.g. onset, duration and pre-programming) but how visual strategies emerge based on information perceived under interacting personal, task and environmental constraints (Renshaw et al., 2019). This approach will offer insight, particularly when exploring golf putting *in situ* or in designing a representative task design. In this case, golf putting can be considered a complex perceptual-cognitive skill owing to unpredictable environmental factors such as the variable putting characteristics influencing the topology and grain of the green. The changing conditions may require a golfer to develop different perceptual-cognitive skills to those required putting in a constant environment, when using a repetitive putt. Therefore, based on an Ecological Dynamics perspective understanding what information an individual is perceiving to regulate actions is critical to be able to understand how perceptual expertise is developed. To enable us to develop greater understanding of perceptual expertise and to explore/test these two alternative theoretical perspectives both representative task designs and more traditional approaches will be used throughout this thesis (Table 1).

Table 1: Breakdown of studies in the thesis relative to theoretical underpinnings and assumptions

Study	Aim	Theoretical Approach	Assumptions Based on Theoretical Approach: Cognitive	Assumptions Based on Theoretical Approach: Ecological Dynamics	Findings	Learning for Future Studies
1	Examining Quiet Eye using a Representative Task Design with highly skilled golfers	Cognitive/ Ecological Dynamics (ED)	QE duration would be longer based on task difficulty and longer QE duration is synonymous with superior performance	The purpose of vision is to view and take notice of the ambient environment and, as a result, each gaze is considered important for performance. Thus proposing QE duration is part of the picture but not the sole factor, therefore QE duration onset and offset will not be the determining factor for performance and other visual strategies will be beneficial.	Shorter QE duration were linked with greater performance. QE duration did not differ as a function of task difficulty, despite performance changing in accordance with task difficulty. Our findings raise important questions surrounding the theoretical underpinnings of QE duration. The enhanced performance for QE on the hole and ball demonstrates the visual strategies used by golfers reflect both near and far aspects of the aiming task of golf putting. In broader terms, the present findings therefore provide support for an ecological approach to the task.	Findings highlight the use of a representative task design is critical to understanding expertise. The findings question the predominant view of why a longer QE duration impacts performance so further theoretical testing is required in Study 2, particularly as limited studies have used representative task design. Participants were not trained in a QE intervention, so important to address whether training is essential to receive the performance benefits. If findings from Study 2 are consistent with Study 1, then future study is required to explore other aspects of perceptual-cognitive expertise (Study 3)
2a	Exploring the impact of a QE intervention on golf putting performance.	Cognitive	QE intervention designed to promote/teach optimal QE duration will improve performance. Performance benefits are associated with longer QE duration.		QE intervention did improve performance. However, performance improvements may be due to practice effects. Other gaze variables in additional to QE duration did change based on the QE intervention.	Further study is needed to i) explore underpinning mechanisms of a longer QE duration (Study 2b); ii) to address issues within the research design (Study 2c) and iii) explore the change in other gaze variables

Study	Aim	Theoretical Approach	Assumptions Based on Theoretical Approach: Cognitive	Assumptions Based on Theoretical Approach: Ecological Dynamics	Findings	Learning for Future Studies
2b	Exploring neural activity, potential QE mechanisms, and golf putting performance	Cognitive	There will be difference in neural activity between QE intervention putts and control putts and as a function of performance.	There will be differences in neural activity as a function of performance, that occur throughout the pre-motor preparation period.	A difference in neural activity for hits was established in comparison to misses with successful shots associated with greater preparation, in comparison to misses.	Further study is required to investigate hits having enhanced and earlier preparation time in relation to misses. The potential applied link to inhibition of left hand/arm is also promising. There are, however, limitations within the methodological design, particularly regarding the feasibility of conducting MRCPs research using representative task designs for golf putting.
2c	Exploring the impact of a QE intervention on performance over multiple sessions.	Cognitive	QE intervention designed to increase QE duration will improve performance.		QE intervention did not improve performance once accounting for practice. These findings are not consistent with a cognitive approach.	These findings question the feasibility of QE duration training, so further research is required to explore other perceptual factors underpinning expertise (Study 2c, 3a,b and 4)
3a	Exploring Perceptual-Cognitive Expertise in golf putting using a screen based task	Cognitive	Expertise will influence gathering information (viewing position), decision making, ability to predict outcome.		The findings revealed that participants could accurately read the green from a 2D image, however, inconsistencies in the accuracies of the green read across the participants and the different putt type existed, although these differences were not related to expertise.	Screen based tasks are not appropriate for measuring expertise or training perceptual-cognitive skill. So further testing is required to explore the perceptual requirements across the whole putt routine with participants hitting the ball (Study 3b, 4).

Study	Aim	Theoretical Approach	Assumptions Based on Theoretical Approach: Cognitive	Assumptions Based on Theoretical Approach: Ecological Dynamics	Findings	Learning for Future Studies
3b	Exploring Perceptual-Cognitive Expertise in golf putting over multiple sessions *in situ*	ED		The reciprocal relationship between golfers, task, and environment will influence perceptual expertise and performance.	We found the golfers (even highly skilled) struggled to read the green correctly and consistently evaluate whether they had read the green accurately. Our findings suggest when the green reading component of the putt is high, performance decreases in comparison to when the green reading requirement is low.	Testing perceptual expertise needs to be conducted using a representative task design (Study 4).
4	Moving towards the development of a Perceptual-Cognitive intervention to improve performance	Cognitive/ED	The intervention will improve performance, as the intervention will provide the right information at the right time on perceptual cues in the environment. The participants will use this information to plan and select the most appropriate motor response.	The intervention will improve performance by giving participants a chance to 'perceive affordances' and to provide the participants with information on functional properties of the environment and the ways that they can act to achieve their task goal.	Findings revealed the intervention did improve putting performance and the golfer's ability to accurately evaluate their read, aim point, pace and execution. However, there were no changes in start line, which is what would be anticipated based on a cognitive approach. The lack of transfer, retention tests and short intervention and time between pre and post do limit these results especially as improvements in performance may simply be due to practice effects.	Expanding the research focus to the whole putting routine, has revealed how multi-faceted perceptual-cognitive expertise is. To enable accurate dissemination, it is recommended that future testing is conducted i) using a representative task design; ii) measures the whole putting routine; and iii) is underpinned by an ecological approach to explore the interaction between the athlete, task and environment.

Chapter 2: Literature Review

To provide context for work presented in this thesis, the current chapter starts with a brief overview into the broad area of sport expertise, followed by a discussion of measuring expertise within golf putting. The second key area to be introduced within this chapter will be a review of literature relating sports performance to visual attention. This section of the literature review will focus upon underlying theories of visual attention and the well-documented visual strategy of 'Quiet Eye' as a specific factor influencing expertise in the context of performance golf putting. The next section of the literature review, will provide a brief general overview of neuroimaging in sport, before specifically focusing on EEG studies in golf putting A final key area of the literature review will focus on perceptual cognitive expertise and the premise of improving performance through a perceptual-cognitive intervention study.

2.1 Overview of Sport Expertise

Sport expertise research aims to identify factors separating exceptional from ordinary performers (Baker et al., 2003). At this stage, sport expertise research has not drawn firm conclusions as to what specific factors distinguish exceptional from ordinary performers (Farrow et al., 2013). Nonetheless, it is broadly accepted that sport expertise is "acquired as a result of successful interaction of biological, psychological and sociological constraints" (Baker et al., 2003).

The demand to understand sport expertise is increasing in line with the pursuit of performance excellence and consequent need for athletes, coaches and sports managers to continually produce performance gains (Farrow et al., 2018). Studying sport expertise enables researchers to explore how expertise is developed and maintained, with the aim of providing guidance to best promote or enhance elite sporting performance. Importantly, for researchers, gaining an explicit understanding of factors underpinning sport expertise allows development of appropriate theory, as well as informing practical dissemination guidelines within sport (Ericsson, 2003). From this perspective, sport expertise research can be viewed as a field of research at the intersection of sport science, exercise psychology and motor control (Farrow et al., 2018).

In sport expertise research there are two main challenges (Farrow et al., 2018). The first challenge lies in the need to measure individual differences within experts, as opposed to the traditional approach of focusing on measuring differences between experts and novices (Abernethy, 1991; Bootsma, 1989). One key reason for focussing primarily on expert performance is that it encourages evaluation of the differences between experts. Whilst the traditional expert versus novice approach measures the average behaviour of different groups; the expert focused approach does not simply treat all experts as a single homogenous group and encourages evaluations of differences between experts. In principle, sports expertise research assumes the evaluation of variability across experts should reveal important differences in the way successful sporting performances can be achieved, thereby highlighting a range of potential factors enabling experts to perform successfully. In practice, recruiting enough experts is often extremely challenging, as Ericsson (2003) notes, experts are by their nature outliers and this inherently means experts are limited in availability.

The second challenge for sport expertise researchers is the requirement to measure actual sporting behaviour whilst maintaining control of extraneous variables. To meet this challenge, researchers are increasingly seeking to create a representative task that can replicate informational constraints of applied competitive performance environments (Dicks et al., 2009). The move towards employing representative tasks is not just a theoretical concern. One notable practical consideration if researchers do not use a representative task design is that expert performance is liable to be affected by 'ceiling effects' (Araújo et al., 2007). A ceiling effect is seen when performance in the experimental test is not sensitive enough to discriminate differences within, or between, individuals. Crucially using a repetitive putt design the laboratory experts may not be able to demonstrate a different visual strategy based on the task design. For example, the surface in the laboratory has fewer visual features than a real green (Figure 1). Furthermore, van Lier, van der Kamp and Savelsbergh (2011) found after fifteen repetitive putts a participant knew the read. In competitions a golfer would not hit repetitive putts, so would be unable to learn the read of the putt through practice. During competitive golf every single putt is unique, requiring an on-line assessment of the problem and the creation of a tailored motor-action solution.

Therefore, it could be argued creating representative conditions is a crucial issue for researchers interested in fully capturing sports expertise.

Figure 1. Comparison of typical 'laboratory study' (Picture A) surface and outdoor green (Picture B).

2.2 Expertise in Golf Putting Studies

2.2.1 Testing Expertise in Golf Putting

Traditionally, for ease of measurement and based on the cognitive approach, putting tasks are completed inside, on highly unrealistic artificial greens (Campbell & Moran, 2014). However, this 'laboratory-based' format does not accurately recreate the perceptual or motor demands occurring in real-world golf (Roca & Williams, 2016). Currently, a wide range of differences exist between putting as carried out in traditional research studies and putting in real-world golf (see Table 2) which have implications of Golfers' Physical Positioning; 2) Task Goal; and 3) Perceptual Requirements.

Table 2. Comparison of the characteristics of a typical putting task used in research versus those occurring in real-world applied performance golf putting.

Research with EEG and Eye tracking	Real-world Golf Putting with Experts
One putt taken repeatedly from one distance	Different putts ranging in complexity
One surface - consistent pace	Changing surface - variable pace
Given a putter	Use of their own professionally fitted putter
Indoor putting	Outdoor putting
Changing the size of the hole	Putting to the regulation size hole
Limited or part of pre performance routine	Full pre performance routine each putt
Restricted putting area - e.g., wall at the end of the indoor putting surface	Open green with distinctive environmental features such as the rough or long grass
Given a ball	Own ball with their own markings
High number of trials/set number	Low number of trials/vary on the day
Use of video feedback	See another person putt on the green

2.2.2 Golfers' Physical Positioning

In van Lier et al's., (2011) 2nd and 3rd experiments, a simple standard peripheral weighted putter was given to all participants. Consequently, the putter was not specifically tailored to the height and putting positions of each participant. This distinction is critical as posture/golfer's positioning significantly impacted on performance (van Lier et al., 2011; van Lier, 2011). Standardised putters are frequently used in research (see Carey et al., 2017 for review) compatible with cognitive approaches as the action response is less important (Renshaw et al., 2019). The impact of posture on performance has been linked to the golfer's head position which in turn influences what information the eyes can detect. The quality and amount of information eyes can detect influences information the visual system can receive and process in order to transform into action (Goodale, 2011). Consequently, poor quality or limited information detected by the eyes can lead to a modified action and/or decrease in performance. In contrast, if the eyes are able to receive good quality information, this can be processed to enable the refinement of action resulting in enhanced performance (Goodale, 2011). Furthermore, Hung (2004) found the type of grip also influenced the golfer's eye and head movements when completing a putting task (20 trials, at 3ft and 9ft), using one of the three different grips; 1) conventional, 2) one handed and 3) cross-hand grip. Findings suggest different putting grips affect eye movement, head rotation variability and putting performance success (% putts holed) across distances. Eye movement and head rotation variability using the conventional grip were significantly higher at both 3ft and 9ft in comparison to two other grips at the same distances. Taken together, based on the results of van Lier et al. (2011) and Hung (2004), it is unclear if using a standardised putter limits participants' ability to pick up and access visual cues and what impact this may have on participants' performance. Therefore, throughout all the studies in the thesis, participants will be asked to use their own putter that has been professionally fitted to them.

2.2.3 Task Goal

The task goal of high-performance putting is to complete minimum number of putts possible during competition and to 'hole out'. In comparison, many previous studies in golf putting have abstract task goals, with repetitive methods using a large number of trials from one spot (Couceiro et al., 2013). Consequently, in the experimental studies presented in this current thesis the task goal is always to complete the putting task in as few shots as possible and to compare how task design influences the ability to measure and understand expertise.

2.2.4 Perceptual Requirements

The majority of putting research has not allowed participants to carry out a full golf putting routine or pursue green reading problems. As a result, there is limited knowledge about where golfers look and what visual information they process when scanning the green (Craig, et al., 2000). Even the skill of green reading is currently under explored in putting research (Carey et al., 2017; Craig et al., 2000). To accurately replicate vision for action and to understand how participants use vision to help them putt successfully, it is important the task is designed in a way that the "critical visual information maps directly onto the response, guiding it in the here and now" (Milner & Goodale, 2008, p. 778). Research which does not allow participants to carry out a normal putting routine, and does not include perceptual cues such as contours, or natural features in the course is inherently not representative. Many of the current study designs have altered or not reported perceptual requirements within their design and this makes it harder to apply the findings in-situ. A common design issue is putting to a non-regulation size hole (see Carey et al., 2017 for review) which changes the motor control elements of the task, influencing the task difficulty. Another common issue is poor putting surface; only three studies report stimp (speed of the green) rating comparable to speed of high performance golf putting (Fairweather et al., 2002; Fairweather & Sanders, 2001; Wilson & Pearcy, 2009). Stimp is important as Fairweather et al. (2002) found not all experts were able to adapt to changes in green that naturally occur within the duration of a competitive round. Furthermore, some researchers have investigated perceptual requirements using virtual environments, to examine the cognitive perceptual skills of applying force (Fery & Ponserre, 2001) and reading the green (Campbell & Moran, 2014). Apart from obvious differences in appearance between virtual and real greens and execution differences between carrying out a virtual putting task and an actual putting task, the wider implications of using virtual environments is unknown (Campbell & Moran, 2014). Further exploration is required to understand how perceptual-cognitive decision making within the virtual environment relates to the equivalent skill in a real-world environment (Dicks et al., 2010).

Adding to the confusion, research has suggested there may be differences in aiming errors depending on where the golfer stands to line their putt up, for example, standing behind the ball or aiming when standing over the ball (DeBroff, 2018) which is typical in most research designs and in DeBroff's (2018) study. When the golfer's aim is over the ball there is a tendency for more errors in alignment from the target line in comparison to when standing behind the ball (DeBroff, 2018). In support of this, van Lier et al's, (2011) study found right-handed golfers had a left bias for their putting alignment errors when aiming standing over the ball. The standing position when aiming could influence the errors in alignment, due to evidence-based selection hypothesis (Clark, 2001). In accordance with this evidence-based selection hypothesis (Clark, 2001), how an individual recognises and selects visual information from the scene is influenced by what they consciously see. What they see then guides their choice of intended action, referred to as conscious visual experience (Clark, 2001). Conscious visual experience (Clark, 2001) is dependent on the individual accessing the scene appropriately in order to plan, recall and assess the best action to take, thus offering one explanation of why research has found there are more errors in alignment when standing over the ball (van Lier et al., 2011).

Additionally, when the golfer views the hole/target standing over the ball, the golfer uses monocular vision and has a narrower field of vision, in comparison to standing behind the ball to aim (Pelz, 1994). When standing behind the ball, the golfer uses binocular vision (Pelz, 1994) so golfers will see different information in the visual scene, based on where they are standing when aiming. If the golfer chooses to use both positions by standing behind the ball and over it, exploring how the golfer combines this information when deciding on their target line is of interest. Consequently, how a golfer decides a target line and associated accuracy of the target line will be explored in more detail in the data chapters of this thesis.

2.3 Visual Attention in Golf Putting

The first part of the chapter will outline what Quiet Eye (QE) is before going on to outline studies which have explored QE in relation to golf putting performance. The final part of this chapter will highlight gaps in literature and consider relevant underpinning theory for visual attention.

Quiet Eye

Over the last twenty-five years Quiet Eye (QE) research has generated much interest, both from academic and applied communities. Vickers (2007) defines QE as:

"The final fixation or tracking gaze that is located on a specific location or object in the visuo-motor workspace within 3° of visual angle for a minimum of 100 ms. The onset of the QE occurs prior to the final movement in the task, and the offset occurs when the gaze deviates off the object or location by more than 3° of visual angle for a minimum of 100 ms. (p. 280)."

2.3.1 Quiet Eye in Golf

QE researchers have made bold claims about the potency of QE for golf putting performance; claiming QE duration is the difference between good performance and poor performance (Vickers, 2004). QE duration has been found to predict 43% of the variance in putting performance in experienced expert golfers (Vine et al., 2011). When exploring QE duration in relation to performance, it appears an earlier onset of QE duration, as well as duration of QE, is critical (Vickers, 2007; Wilson & Pearcy, 2009). To have an earlier onset means higher skilled golfers have a slightly different pre performance routine in comparison to less skilled golfers. Adaptation to the pre performance routine is incorporated into QE intervention training instructions (below), with clear guidance about when onset should start (Vickers, 2007; Harle & Vickers, 2001). The QE training protocol (Vine & Wilson, 2010, p.366) advised participants to:

- Assume your stance, align your club so the gaze is on the back of the ball.
- After setting up over the ball, fix your gaze on the hole. Fixations towards the hole should be made no more than 3 times.
- The final fixation should be a QE on the back of the ball. The onset of QE should occur before the stroke begins and last for 2 to 3 seconds.
- No gaze should be directed to the club head during the backswing or the foreswing.
- The QE should remain on the green for 200 to 300ms after the club contacts the ball.

In support of earlier onset, plus optimal QE duration, QE training has improved putting performance by 1.9 putts per round across ten competitive rounds with expert (handicap average 2.78) golf players (Vine et al., 2011). In contrast, in the same study a control group with expert golfers (comparable handicap) did not improve performance in ten competition rounds (Vine et al., 2011). Participants completed an intervention involving participants from both groups (QE training and control), observing gaze behaviour and commenting on gaze control. After performing five putts (gaze and performance measured), participants from both groups observed a video of their own gaze behaviour alongside an elite visual gaze example (Vickers, 2007). In the QE training group, researchers explicitly promoted understanding of characteristics of expert visual gaze via questions and answers; in the control group only, the video was observed. Both groups then performed a further 15 putts, where gaze and performance measures were recorded and the QE training group were asked to follow the QE training protocol consistent with previous literature (listed above).

Using an artificial putting surface to a circular target (5cm radius) on an artificial putting surface, Vine & Wilson (2010) tested fourteen novice participants performing 480 10ft putts over eight days. The central target was surrounded by nine concentric circles (increasing by 5 cm in radius) allowing a measure of performance error to be recorded. Participants used standardised putters and golf balls, provided by researchers for all testing, completing a pre-test and demonstrating no difference in performance between groups. After the pre-test participants were randomly allocated to a QE training or control group. Participants in the QE training group were asked to follow the QE protocol described above (consistent with previous research) and participants in the control group were asked to focus and follow the technical instructions outlined below, as outlined by Vine & Wilson, (2010 p. 366):

- Stand with your legs hip-width apart and keep your head still.
- Maintain relaxation of the shoulders and arms.
- Keep the putter head square to the ball.
- Perform a pendulum-like swing and accelerate through the ball
- Maintain a still head after contact.

Participants began an assigned training regime (QE or control), performing a further 80 putts (2 blocks of 40) on the same day as the pre-test. On Days two and three of testing, three blocks of 40 putts were then performed to complete a total of 320 acquisition putts. On Day 5 participants performed a retention test, consisting of a single block of 40 putts without the guidance associated with their training regime. During testing participants were told their scores from the retention test on day one would put them in the bottom 30% compared to those who had already taken part in the competition and were told to attempt to improve their performance or the data would not be used during the study. On Day 8 participants performed a transfer (pressure) test, consisting of 40 competition putts, aimed at manipulating levels of cognitive anxiety. A prize of £50 for the best individual score was on offer for competition putts and participants were informed their scores from the competition putts were going to be compared with other participants and perhaps used as part of a student presentation. Finally, following the pressure test, participants performed a second retention test (identical to Retention Test 1) to form the typically adopted A-B-A (retention-transfer (pressure)-retention) design across 120 putts (Lam et al., 2009).

Findings suggested the QE-trained group did not perform better than the control group in retention tests 1 and 2 despite having significantly longer QE periods. In the pressure test, the QE-trained group performed significantly better compared to the control group. The authors concluded, “QE training may provide a useful method to guide visuomotor skill training and a psychological technique to aid performance under pressure” (Vine & Wilson, 2010, p. 374).

Support for these findings has come from another training study using novice golfers, which found the QE trained group had superior performance to the technically trained group (Moore, et al., 2012). In Moore 's (2012) study forty novice golfers (M age = 19.55 ± 1.65 years) volunteered to participate. Participants were given a standardised putter and golf balls then randomly assigned to the technical or QE trained group for all testing. Participants first completed 40 pre-test 10ft putts from 3 different locations, then completed acquisition putts: Day 1 Training 2 x 40 putts; Days 2+3 3 x 40 putts where they learnt their specific interventions. On Day 4 participants completed a retention test of 20 putts and then on Day 5 they completed 20 x competition putts in the pressure test followed by 20 putts as second retention test.

The findings at the pre-test revealed no significant differences between groups for QE duration. Findings from the competitive testing revealed the QE trained group holed a higher percentage of putts in comparison to the technical trained group; with the QE trained group holing 7.5% more putts. The QE trained group were also more accurate on missed putts (10cm closer to the target on missed putts) in comparison to the technically trained group. A significant difference between the groups in the retention and pressure test was noted, with the QE trained group having longer QE durations during retention and pressure tests. The QE trained group performed consistently in the retention and pressure test, with no differences between mean radial error across tests (both $p > .08$). In comparison, the technically trained group did not perform consistently and experienced a decline in performance for the pressure test in comparison to the retention test (both $p < .05$), suggesting that QE training helps novice golfers learn to putt more effectively than when learning through standard technical training instruction. In summary, the research suggests two main assumptions can be applied to QE in golf putting performance.

1. A longer QE duration improves performance (consistent for higher skilled and novices). The optimal/recommended QE being 2-3 seconds for golf putting.
2. Experts have earlier onset of QE and longer duration of QE in comparison to lesser skilled golfers.

2.3.2 Gaps in the QE literature

In this review several gaps within the existing literature have been identified and broadly categorised into six topic areas. This next section will discuss each gap in turn including the practical and theoretical implications.

QE in context with other visual studies

Setting a one size fits all recommendation appears to ignore the fact fixation durations are idiosyncratic (Holmqvist, & Andersson, 2017; Yarbus, 1967). The idiosyncratic nature of QE durations in golfers is currently not well understood as previous research has typically not reported QE duration on a trial by trial basis, or variations between and within individuals (Rienhoff et al., 2016). In addition, studies do not report information about saccades, including number of saccades or gaze sequencing profile. Saccadic eye movements provide what can be described as a series of ‘snapshots’ of the visual environment in an attempt to create a stable perceptual experience (Cronin & Irwin, 2018). Saccades typically are 30-80ms in duration (Holmqvist, & Andersson, 2017). ‘Snapshot’ occurs when eyes move from one object to another object. To retain information on visual features in the environment there is a brief pause to enable information to be sent and stored in visual working memory (Holmqvist, & Andersson, 2017). This pause is referred to as saccadic suppression (Volkmann, 1986) and it allows a continual stable representation of the world to be formed in visual working memory (Cronin & Irwin, 2018).

In the QE intervention studies, participants complete straight putts and are asked to view the target but given no guidance on where to look and for how long (Vine & Wilson, 2010). Recognising the type of putt is important as the saccades out to the hole for a straight putt are different in profile to those of a sloped putt, whereby the saccades include the breakpoint and the target (Pelz, 1994). The ambiguity of the instructions given to participants may be problematic as previous eye tracking studies have found the instructions given impact on where an individual looks in the scene and the scan pattern they adopt (Tatler et al., 2010; Yarbus, 1967). This has important implications as it is unclear if the gaze behaviour that is measured within the QE intervention studies is similar or different to that of the gaze behaviour that a participant would adopt in the real-world golf competition.

QE in-situ, using a representative task design

To date, most QE studies have measured gaze behaviours on an artificial surface, with repetitive straight putts from 3ft, 6ft, and 10ft in a laboratory setting (Table 3). The only study which instructed the participants to complete the trials individually had a shorter QE duration in comparison to the other studies. In other studies, participants completed the putts consecutively without moving their feet in between trials and not completing their full pre shot routine.

Table 3. Overview of associated QE duration based on the task design.

Paper	**Putt Distance**	**Task**	**Mean QE**
Vickers (1992)	3m approx. 10ft	Repetitive putts completed consecutively. One distance. Straight putt	2200ms
van Lier et. al., (2010)	6ft	Repetitive Putt. One distance, three putt type (0%, 1 %, 2% slope). Putt trial performed individually.	1080ms
Mann et. al., (2011)	12ft	Repetitive putts completed consecutively. One distance. Straight putt	3330ms
Vine et. al., (2011)	10ft	Repetitive putts completed consecutively. One distance. Straight putt	2794ms

Individual differences in QE and performance.

The potential for QE duration to differentiate between successful and unsuccessful putts on a single trial basis and successful and unsuccessful putts within individuals, including experts has been noted as one of the main ways to progress the current literature base in several reviews (e.g., Rienhoff et al., 2016; Vickers, 2007). Despite the potential to use the measure of QE duration in this way there are limited studies that focus on differences within individual trials or within individuals. Two studies which did explore individual differences (Mann et al., 2011; Panchuk et al., 2014) found on an individual level, QE duration did not account for performance across all participants.

Influence of Task Difficulty

Currently in golf putting, two studies have examined the influence of task difficulty on QE. Wilson and Pearcy (2009) found University team golfers completing putts of 3m in length, on an indoor artificial surface, had longer mean QE duration for the successful straight putts in comparison to the successful sloped putts, meaning QE duration was longer for the ‘easier’ task. In contrast Walters-Symons et al. (2017) found QE duration did increase as the task complexity increased. However, to manipulate task difficulty, the authors modified the golf putting task (by altering the target size, altering the length of the golf putt and altering the size of the effective putter face) meaning it is difficult to evaluate how task difficulty impacts on QE duration and performance relative to applied golf.

In studies examining the influence of task difficulty on QE duration outside of the golf putting context, QE durations have been found to increase based on the complexity (Williams et al., 2002). However, Klostermann et al. (2013) found a longer QE duration has been found to be beneficial for performance under high task demands. At this stage it seems the optimal duration may depend on specific tasks constraints (Rienhoff et al., 2016). Further research is required utilising a representative task design to effectively assess the impact of task difficult on QE duration and if appropriate performance.

Is it more beneficial to look at the hole, the ball or both before putting?
Competitive golf putting is a near and far aiming task which involves accounting for the temporal factors, distance, force and velocity that needs to be applied to accurately perform the skill (Williams et al., 2002). The near component is the ball, and the far aspect is the hole. Currently research in golf putting has focused on the ball, but research in other sports have suggested looking at the target rather than QE duration may be critical for optimal aiming (Klostermann et al., 2014; Oudejans et al., 2002). Furthermore, research has found when visual attention is focused on a far target in addition or instead of the near target the participant gains key information to help successfully complete the task (Cañal-Bruland et al., 2011; Craig et al., 2000; Oudejans et al., 2002).

Proteau (1992) suggests in complex tasks it is critical to use central vision to view near and far targets to develop movement accuracy. A longer fixation using central vision (rather than saccades out to the hole) gives the individual time to develop an accurate representation of the visual scene so that decision on speed and distance can be made (Spering & Montagnini, 2011). Therefore, to explore the near and far aspect of putting, the influence of visual strategies on the hole and ball on performance is something that will be explored in Chapter 3.

How does QE impact performance in-situ?
Golf putting gaze behaviours in-situ have not been measured so currently it is unknown whether world class golf players adhere to the QE training intervention instructions listed above or, whether they adopt different gaze behaviours when in-situ. It is speculated that gaze behaviours in-situ will be different due to the different demand constraints and due to increased visual information to process within the visuomotor workspaces across the variety of putts and green

topographies. Competitive golf requires the player to adapt to changes in environmental conditions including; green landscapes, green speed, temperature, wind and distance and it is the ability to perform and adapt to the less certain conditions which makes putting a challenging skill to perform (Mackenzie & Sprigings, 2005). Therefore the studies in this thesis will use a range of methodological designs with the aim to create successful transfer from research to practice and test current recommendations to explain how and why QE works, or crucially why current recommendations are producing inconsistent results.

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2.3.3 Theoretical Underpinning mechanisms of Quiet Eye

Currently there is not a clear theoretical understanding of why QE works and there has been a call for further research into understanding QE and its functional mechanisms (Causer et al., 2010).QE has been dominated by an information-processing perspective towards cognition (Rienhoff et al., 2016), however, two other approaches have also been presented in this section, as part of the wider discussion on the pending theoretical underpinnings of QE (Vickers, 2016).

Cognitive Programming

A longer QE may enhance performance due to a longer period for cognitive programming (Vickers, 1996; 2007; Williams et al., 2002). This is based on the location-suppression hypothesis proposed by Vickers (1996). Cognitive programming enables the individual to finalise the parameters of the movement; account for relevant environmental cues and synchronise motor strategies (Mann et al., 2007). In support of the cognitive model, current QE training interventions include time for the individual to complete cognitive programming prior to execution (Vickers, 2007). Likewise, QE has also been reported as a measure of attentional control in visuomotor tasks (Mann et al., 2007) based on the assumption that QE reflects the efficiency of visual attention (Janelle, 2000) and effective orientation of vision has been linked to optimal attention (Vickers, 2007). Experts have been found to have longer fixations, which allows greater processing in comparison to shorter fixations for novices (Vickers, 2007). However, in contrast as previously mentioned it has been found that QE duration is not always longer for harder tasks (Wilson & Pearcy, 2009) and a longer QE duration does not always lead to performance benefits (Farrow & Panchuk, 2016)- findings that can't be explained by the cognitive programming approach.

Attentional Control Theory

Attentional Control Theory (ACT) (Eysenck et al., 2007) has been adopted as a theoretical framework to explain how anxiety affects the QE and subsequent performance. ACT has been designed as an extension to Processing Efficient Theory (PET) (Eysenck & Calvo, 1992). According to the PET theory, (Eysenck & Calvo, 1992) when anxious an individual allocates their attention to detect and potentially deal with the source of the threat (i.e., potentially task irrelevant stimuli), instead of allocating their attention to task-relevant stimuli (see Wilson, 2008 and 2012 for reviews). In support of the theory it has been found performance in the high anxiety condition declined and participants had shorter QE durations, less efficient movement kinematics in comparison to the low anxiety conditions (Wilson et al., 2009). Furthermore, when feeling anxious participants changed their gaze pattern (Wilson et al., 2009) and reported an inability to focus on the target location long enough to process relevant information sources (Behan & Wilson, 2008; Wilson et al., 2009). These findings would suggest anxiety disrupted an individual's attention state and the individual was less able to focus on a target which reduced their ability to achieve an optimal QE duration (Causer et al., 2011).

In contrast, there is now a growing evidence base suggesting anxiety does not always have a detrimental effect on performance and change visual strategies. For example, research exploring the impact of anxiety on QE in skilled dart players suggested reductions in final fixations only have a detrimental effect on performance if they reduce beyond a critical threshold point (Nibbeling et al., 2012). Nibbeling et al. (2012) did not define the critical threshold point in their study, however the skilled dart players maintained a successful performance in the high anxiety condition with a minimum QE duration of 1250ms. This is supported by research using a driving task, which found there were no differences in performance or visual strategies adopted in the high or low anxiety conditions. More specifically the authors reported when individuals were anxious they allocated more resources to the task and this ensured their performance did not deteriorate (Murray & Janelle, 2003). These findings cannot be explained via the

ACT (Eysenck et al., 2007) and suggest ACT could only partially explain why QE works but cannot account for the underpinning mechanisms behind QE.

Ecological Perspective

In this approach the purpose of vision is to view and take notice of the ambient environment and as a result each gaze is considered to be important (Gibson, 2015). Support for the effectiveness of each gaze for enhancing performance was found by Oudejans et al. (2002), who found the time the individual sees the target for has a bigger impact on performance than QE duration. Likewise, increasing total viewing time on the target allows the individual to pick up key information relative to the environmental constraints (Oudejans et al., 2002). Again, this has important implications for current golf putting research as predominately only QE duration measures are reported. It is proposed to gain a greater understanding of how visual strategies influence performance additional measures of gaze strategy will be recorded.

Golf putting is a complex skill and there is a dynamic interplay between perception, cognition, and action. The person's experience in the environment does influence how the individual processes the world around them; how they act and subsequent motor action. At this stage there is a lack of clarity of how the environment influences the golfer's actions and motor performance. It is not clear how the golfer makes a decision in an environment that is ever changing to successfully complete their goal directed behaviour. As previously discussed, when putting as part of their pre-shot routine, the golfer will saccade out to the target and back to the ball several times and then they will hold their vision still on the back of the ball just prior to putting. However, at this stage, it is unclear what type of information the golfer is picking up at each stage of their routine and how effective this information is in helping the golfer to successfully perform (Craig et al., 2000). Currently, the majority of existing golf putting research has taken place using non-representative designs and comparing this environment to a more representative environment can help to explore how a golfer uses information in the scene when putting.

Neural Perspective

Current research into the neural perspective is in-line with the neural system proposed by Corbetta and Shulman (2002) who describe two separate cortico-cortical neural systems and their role in attending to environmental stimuli. The first cortico-cortical neural system is a dorsal frontoparietal network and the dorsal system is pre-activated and guided by the expectation of seeing an object at a particular location or seeing certain features in the environment. When the individual sees the object or feature this triggers the preparation of a specific response. The first stage in preparing a response is to commit the visual scene to short term memory, then this information is used to generate current goals and appropriate selection of stimuli (feature locations/objects) to be processed. The second neural system described in the model proposed by Corbetta and Shulman (2002) is the ventral frontoparietal network, which is different to the dorsal frontoparietal network as it is not activated by expectations, but when an unexpected relevant target is recognised in unattended areas. When the target is recognised the individual is required to re-orientate their attention and both systems are active in this stage. The ventral network interrupts, as a "circuit breaker", to ongoing selection in the dorsal network, which in turn shifts attention toward the novel object of interest. Thus highlighting how the system aids an individual to plan a motor response, adapt a plan or even in some cases predict/anticipate a response based on their previous experience of the environment, recognition of perceptual cues and perception action coupling (Corbetta et al., 2008).

2.4 Neural Activity and Golf Putting Performance

EEG technology has been successfully used within target sports research (Del Percio et al., 2008). EEG is suited to measuring sports behaviour as it provides a higher temporal resolution, by measuring in milliseconds, in comparison to other imaging techniques. The higher temporal resolution offers a way to measure complex sports behaviour performed in a short period. The neural activity can be segmented by times, allowing for behaviours to be categorised, for example, pre and post the shot and specific epochs of time, such as, one second prior to the initiation of the movement/shot execution. Time windows can be matched to the self-paced pre performance routine prior to the motor execution.

2.4.1 EEG in golf putting

Golf putting is therefore suitable for EEG, particularly as there are limited movement artifacts during the pre-shot routine as the golfer's feet are still and the motor action requires a fine movement. Observation of the golf putting action indicates that head and eye movement may be problematic, however, previous research has not reported any concerns or data loss due to head/eye artifacts. Current research into EEG in golf putting has focused on four main themes, 1) neural efficiency hypothesis 2) alpha oscillations related to performance, 3) theta oscillations related to performance, 4) beta oscillations related to performance.

The neural efficiency hypothesis

The neural efficiency hypothesis of psychomotor performance was proposed by Del Percio et al. (2008) and Hatfield and Kerick (2007), and is based on findings in research which highlighted expert athletes' completed tasks with minimal effort in comparison to the novice athletes and proposes an inverse relationship between performance effectiveness and resource allocation (Bertollo et al., 2016 . There are two distinct features: i) reduction in neural activity as the skill execution becomes more automatic ii) reduction in activity in the sensory motor cortex (Bertollo et al., 2016). Reduction in activity reflects efficient processing and adaptive information processing during motor execution (Callan & Naito, 2014; Cheng et al., 2015). EEG techniques have been used to measure 'neural efficiency' in research (Del Percio et al., 2008). More specifically Event Related Desynchronization (ERD)/ Event Related Synchronization (ERS) has been proposed as a way to measure neural efficiency (Del Percio et al., 2008). ERD/ERS is defined as the percentage of power decrease (activation) or increase (inhibition) from baseline (Pfurtscheller & Lopes da Silva, 1999). In support of the neural efficiency hypothesis, research has found a decrease in alpha (8-12 Hz) power in frontocentral region for successful putts in comparison to unsuccessful putts with expert golfers (Babiloni et al., 2008). The authors concluded visuo-spatial areas were involved in the process of golf putting and related to golf putting performance. In support of these findings, Cooke *et al.* (2014) also found that experts displayed greater alpha ERD in the final two seconds leading up to the putt in comparison to novices. However, in some sport studies (e.g. Bertollo et al., 2016) a different definition of ERD/ERS has been used, due to the use of ASA software (ANT Software BV, Enschede, Netherlands). ERD/ERS in ASA is defined based on Zanow and Knösche (2004) definition that states ERD is a relative increase of signal power, whereas ERS is a relative decrease of signal power with respect to the baseline. Thus, leading to confusion when interpreting the results.

Theta oscillations

Theta, in particular frontal midline, has also been linked to superior golf putting performance (Kao et al., 2013; Reinecke et al., 2011). More specifically a difference in frontal theta for successful and unsuccessful putts has been reported (Reinecke et al., 2011). This is supported by Kao et al. (2013), who found theta power was significantly lower for the 15 best putts, in comparison to 15 worst putts at frontal, central, parietal and occipital areas. It is likely theta (particularly frontal midline) is involved in the planning and initiation of motor control and it has been specifically linked to learning information about the environment through sensory stimuli (Wyble et al., 2004). Therefore, lower theta power for hits would be expected as it is believed theta plays an important role in priming the motor system and is in-line with the tenets of the sensorimotor integration hypothesis (Bland & Oddie, 2001). In this case theta acts as a readiness signal and is not required in the initiation of task execution. Bland and Oddie (2001) state theta is not essential in the final 200-300m of performance. In contrast other research has found relative increases in frontal midline theta is related to expert performance in golf/shooting (Baumeister et al., 2008; di Fronso et al., 2018; Doppelmayr et al., 2008). Further research is required to explore the link between theta oscillations and performance.

Alpha oscillations

Alpha rhythms are believed to play a role in cognitive processing (Klimesch et al., 2007), specifically involved in the active transfer and processing of sensorimotor information among cortical and thalamic structures (Pfurtscheller & Lopes da Silva, 1999). From a putting perspective, the findings have been inconsistent in concluding whether an increase or decrease in alpha power is related to expertise and/or successful golf putting performances (Balbilioni et al., 2008; Del Percio et al., 2009; Baumesiter, et al., 2008; Cooke et al., 2014) additionally, two studies also found no significant differences in alpha power (Cooke et al., 2015). For this review, the specifics of golf putting studies which have explored the relationship between alpha and putting performance will be explored in more detail in Tables 4 and 5. The ambiguous nature of how alpha is related to golf putting performance, especially in experts, may be in part due to methodological considerations, such as changing the size of the hole (Babiloni et al., 2008) and giving participants a standardised putter (Cooke et al., 2014). Changing the task can reduce the familiarisation and change sensory information and feedback that the participants receive from the task. There is also inconsistency in the number of electrodes chosen, recording equipment, choice of analysis including choice of filtering and baseline (Table 4, 5), these factors do not help study replication of results across golf putting performance.

Beta oscillations

Studying beta oscillations within movement and motor control has been extensively covered since Berger's seminal work on sensorimotor rhythms in 1929 (Berger, 1929). Beta power in sensorimotor task, in particular tasks requiring accuracy, is lower during task execution and increases again once the movement has finished and the posture becomes stable (Kilavik et al., 2013). The decrease in movement related power tends to be bilateral over sensorimotor areas, however, the precise cortical localisation is presently unclear (Kilavik et al., 2013). It is proposed this decrease in beta power reflects the activation of the sensorimotor networks (Pfurtscheller & Lopes da Silva, 1999) and indicates beta's involvement in both the planning and processing, including sensory and cognitive aspects, as well as the movement of the action (Pfurtscheller et al., 2003). From a golf putting perspective, expertise has been linked with greater beta power in the final seconds preceding golf putts (Cooke et al., 2015).

Table 4. Overview of Representative Task Design in EEG Golf Putting Studies (excluding neurofeedback studies).

Study	Participants	Handicap	Playing	Putter Ball	Green Surface	Hole Size	Study Task
Babiloni et al (2008)	N = 12 (7 men, 5 female) Expert	Not stated	>8 years 5x per week, hours Not stated	Not stated	Provided by Italian federation of golf	Diameters 108mm (standard), 80mm, 60mm	100 putts, 15 secs interval, 10 recording blocks with 90 secs between blocks, self-paced and advised to start putting when felt ready
Babiloni et al (2011)	N = 12 (7 men, 5 female) Expert	Not stated	>8 years 5x per week, hours Not stated	Not stated	Provided by Italian federation of golf	Diameters 108mm (standard), 80mm, 60mm	100 putts, 15 secs interval, 10 recording blocks with 90 secs between blocks, self-paced and advised to start putting when felt ready
Baumeister & Reinecke (2008)	N= 18 Amateur	Expert 8.3 +-7.5 years. Novice no formal handicap stated	Expert 7.6 years +-4.2, Expert 13 +-7 hours per week Novices no playing experience	Standardised putter UG-LE Ping USA Bridgestone USA provided	Artificial carpet stimp rating= 9	Standardised	Lying relaxation 10 mins, EEG recorded 2 mins, putt 4 mins at own pace, 2 min seated rest - repeated x5
Cheng, Huang, Chang, Koester, Schack, Hung (2015)	N = 16 (14 male and 2 female) Expert	0 (3.90)	9.5 (2.67), 9.2 (1.83) Current hours not stated	Not stated	Not stated	10.8cm	8 neurofeedback session 12 training trials
Cooke et al (2014)	N= 20 N= 20 (All male) Expert and Novice	Expert <5 with M= 1.5; novice no formal handicap	Expert M= 11.25 years, Novice M= 1.85 years Current hours not stated	90cm blade style golf putter Titleist Scotty Cameron Circa 62 Dunlop DDH for familiarisation. Titleist pro v1	Artificial putting mat Patiograss	Expert 5.4cm diameter, novice standard 10.4cm diameter, wall 0.7m from hole	2-hour testing session, 2 blocks of 60 putts, 17-25secs between each Putt
Cooke et al (2015)	Same as Cooke *et al.* (2014)	Same as Cooke *et al.* (2014)	Same as Cooke *et al.* (2014)	Same as Cooke *et al.* (2014)	Same as Cooke *et al.* (2014)	Same as Cooke *et al.* (2014)	Same as Cooke *et al.* (2014)
Gallicchio, Cooke, Ring (2016)	Ten expert and 10 Novice Right-handed	Expert M = 1.50 golf handicap. Novice: no handicap	Experts M = 11.25 Novice: M = 1.85 years golf experience;	Titleist pro v1 for low and high-pressure tests Putter not stated	Flat putting mat	Hole with a diameter of 5.4 cm (experts) and 10.8 cm (novices)	60 2.4m putts under each of two counterbalanced pressure conditions:, High pressure at cash prize.
Gallicchio, Cooke, Ring (2017)	12 right-handed golfers (age: M = 21 years;)	Recreational (handicap: M = 23, SD = 4.62)	4.63 years (SD = 2.89)	Golf balls (diameter 4.7 cm) using a blade-style putter (length 90 cm).	Artificial flat putting surface (Turftiles)	Hole (diameter 10.8 cm)	2.4m putts. Test-practice-retest design. 3 days of practice (1hr- 12x 5min block). Test = 20 familiarisation putts followed by 50 test putts

Study	Participants	Handicap	Playing	Putter Ball	Green Surface	Hole Size	Study Task
Gallicchio, Cooke, Ring (2018)	Ten experts (age: M = 13 20.90, SD = 0.74; Ten novices (age: M = 19.00, SD = 0.66 years);	Expert handicap: M = 1.50, SD = 2.32) Novice: no formal handicap)	Expert: experience: M = 11.25, SD = 3.78 years Novice experience: M = 1.85, SD = 2.49 years;	Golf balls (diameter 4.7 cm). A blade-style putter (length 90 cm).	Artificial flat putting surface (Turftiles)	Hole with a diameter of 5.4cm (experts) and 10.8 cm (novices)	Task familiarization (20 putts), participants putted 60 balls 3 in each of two counter-balanced pressure conditions
Ji, Wang, Zheng, Hua, Zhang (2019)	N= 20 (All male) Expert and Novice	Expert <5 with a M= 1.5. Novice no formal handicap	Expert M= 11.25 years, Novice M= 1.85 years Current hours not stated	90cm blade style golf putter Titleist Scotty Cameron Circa 62 Dunlop DDH for familiarisation. Titleist pro v1 for low and high-pressure tests	Artificial putting mat 'Patiograss'	Expert 5.4cm diameter, Novice standard 10.4cm diameter, wall 0.7m from hole	2-hour testing session, 2 blocks of 60 putts, 17-25secs between each putt
Kao, Huang & Huang (2013)	*N* = 12 (6 professional and 6 amateur) Gender Not stated	Not stated	Not stated years or practice hours	Standardised putter given (brand Not stated) Balls not stated	Artificial simulator 300mm x 300mm 2 mm in putt distance	Modified 80mm and 60mm	80 continuous putts
Reinecke et al (2011)	*N* = 20 (all male), 2 participants removed due to artifacts	7.9 sd 6.4	10.8 years sd 5.4 Not stated current practice.	Not stated	Artificial green simulator	Not stated	100 self-paced putts, allowed to sit down after every 10 putts
Ring et al (2015)	N= 11 (All Male) Low amateur	28.4 +/- 11.9	3.5 +/- 2.4 years 4.6 +/- 3.5 hours per week	Standardised putter UG-LE Ping USA Bridgestone USA provided	Field = straight putting green on course. Lab = green carpet stimp reading 9	Standardised	10 mins relaxation lying, 2 mins putting from 3m (field or lab), no practice putts, no feedback, 2 min resting period sitting, 2 mins putting from 3m (field or lab), 2 min rest sitting

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Table 5. Overview of Differences in EEG analysis across the studies in golf putting (excluding neurofeedback studies).

Study	Brand of EEG	Number of electrodes	Filters	Data lost	Reference	Trigger	Baseline used	Epoch duration	Unit of Measurement	Electrodes selected
Babiloni *et al.* (2008)	EB-Neuro Be-plus Firenze Italy, 10-10 system	56	Bandpass 0.1-100 Hz sampling rate 2.56 Hz	Only selected artifact free trials but number not stated, autoregressive method used	Not stated	Sam PuttLab	-5 to -4 seconds	-1 second before impact	ERD/ERS	FZ, FCZ, C3, CZ, C4
Babiloni *et al.* (2011)	EB-Neuro Be-plus Firenze Italy, 10-10 system	56	Bandpass 0.1-100 Hz sampling rate 2.56 Hz	Only selected artifact free trials, M= for successful group 42.9% and failures group 26.6%, autoregressive method used	Not stated	Sam PuttLab	-5 to -4 seconds	-5 to +5 second	EEG coherence	P3-F3, P3-C3, P3-T3, P3-O1, P4-F4, P4-C4, P4-T4, P4-O2 electrode pairs
Baumeister & Reinecke (2008)	ElectroCap USA	13	Bandpass filtered at 0.86 Hz	Not stated	Average reference from CZ	Not stated	Not stated	Not stated	Power (µV2)	FZ, F3, F4, CZ, C3, C4, PZ, P3, P4, T3, T4, T5, T6
Cheng *et al*. (2015)	Neurscan	32 + 4	Bandpass 1-100Hz and notch 60 Hz	Not stated	A1 in session then linked ears	Infrared on backswing	Not stated	Not stated	Power (µV2)	Cz
Cooke *et al*. (2014)	ActiveTwo BioSemi Amsterdam	16	1-50 Hz	Average of 114 trials per participant retained	Average	Not stated	Neutral EEG baseline	-5 to +1 seconds,	Power (µV2)	FZ, F3, F4, CZ, C3, C4
Cooke *et al.* (2015)	ActiveTwo BioSemi Amsterdam	16	1-50 Hz	Average of 114 trials per participant retained	Average	Not stated	Neutral EEG baseline stated	5 seconds (- 4 to + 1 second)	Power (µV2)	FZ, F3, F4, CZ, C3, C4
Gallicchio *et al.* (2016)	ActiveTwo BioSemi Amsterdam	16	1-50 Hz	Not stated	Average	Optical sensor	Not stated	-4 to +1 s	Temporal-frontal connectivity using high alpha Inter Site Phase Clustering (ISPC)	(T7) - frontal (Fz) (T8) - frontal (Fz)
Gallicchio *et al.* (2017)	ActiveTwo recording system (Biosemi, the Netherlands)	32	1- to 35-Hz band-pass filtered	Not stated	Average	Optical sensor	Not stated	−3.25 to +1.25 s	Power (µV2)	FC5, T7, CP5, FC1, C3, CP1, F3, Fz, F4, FC2, C4, CP2, FC6, T8, CP6), O1, Oz, O2

Study	Brand of EEG	Number of electrodes	Filters	Data lost	Reference	Trigger	Baseline used	Epoch duration	Unit of Measurement	Electrodes selected
Gallicchio *et al.* (2018)	ActiveTwo recording system (Biosemi, the Netherlands)	Three pairs of Ag-AgCl electrodes	0.1 to 17 30 Hz	Not stated	Not stated	Not stated	Not stated	–9 to +3 s	EOG	FP1 and FP2
Ji *et al.* (2019)	Emotiv 128Hz 14 electrodes	14	Not stated	Not stated	Not stated	Inertial mocap sensors	Not stated	-5 seconds prior to shot execution	Power (μV2)	AF3 AF4, F3 F4, F7, F8, FC5 FC6, T7, T8, P7, P8, 01 02
Kao *et al.* (2013)	Quick-Cap Neuroscan	32	Bandpass filter 1-30 Hz, DC 70 Hz and 60 Hz notchfilter	Not stated	Average mastoid	Not stated	Baseline corrected based on entire sweep	-3 seconds prior to shot execution	Power (μV2)	FZ, CZ, PZ, OZ
Mann *et al*. (2011)	BIOPAC EEG amplifier (EEG100B; BIOPAC Systems, Inc., Santa Barbara, CA	6 silver/silver chloride (Ag/AgCl)			Average mastoid	Not stated	Not stated	Not stated	MRCPs	C3, Cz, C4, P3, P4, FPz
Reinecke *et al*. (2011)	ElectroCap USA	17 with 4 removed due to artifacts	Highpass = 0.86 Hz	Field and lab putting >80%, resting >93%	Average	Not stated	Not stated	Not stated	Power- power values log transformed	Theta only FZ, F3, F4 and Alpha only PZ, P3, P4
Ring *et al*. (2015)	Not stated	16	1-50 Hz	Not stated	Average mastoid	Not stated	Baseline subtraction	-4 to +1 seconds	Power (μV2) in high alpha band only	F3, F4, CZ

2.5 Perceptual Cognitive Expertise in Sport

The area of perceptual-cognitive expertise in sport has been defined by Mann *et al.* (2007) in their meta-analysis as:

> *"The ability to identify and acquire environmental information for integration with existing knowledge such that appropriate responses can be selected and executed"* (Marteniuk, 1976, p. 457).

This definition is consistent with a cognitive approach, whereby highly skilled athletes (experts) are more adept in comparison to lesser skilled athletes in translating *'perceptual cues'* into action (Mann et al., 2007). When tested, highly skilled athletes demonstrate superior ability in perceptual-cognitive expertise, demonstrating specialised skills in visual acuity, contrast sensitivity and depth perception in comparison to less skilled athletes (Hadlow et al., 2018). It is believed these skills enhance the decision making process of choosing the most appropriate action, in turn leading to greater future success (Hadlow et al., 2018). Based on the principles of perception enhancing action, perceptual-cognitive training works on the premise that improving an individual's ability to 'pick up', interpret relevant contextual and situational information enhances performance (Hadlow et al., 2018).

The golfer's decision making process requires cognitive effort to understand and successfully demonstrate perceptual and motor control in order to hole the putt (Sherwood & Lee, 2003). To improve the decision-making process and transfer learning from situation to situation, learning from the initial conditions, response specification and feedback of the sensory consequences post movement and the outcome/ results of the movement need to be linked. Before a movement is initiated, an individual will use recall schema to help form or alter a new schema. Recall schema takes into consideration initial conditions (what is the task?, what are the environmental conditions and what condition am I in; tired, fresh, stressed) and response specifications (how hard do I need to hit this putt, what techniques will produce the best results?). If an individual does not have the ability to accurately assess the initial conditions and response requirements their success in the movement will be limited. After execution of a movement, an individual's programme parameters and generalised motor programmes are updated through recognition schema. Recognition schema will establish movement feedback and error detection to correct responses for the future. Reduced feedback limits the individual's ability to set appropriate programme parameters and ability to transfer the knowledge (Wulf et al., 1993). If the recognition schema is not accurate then a golfer will not recognise the reason, they missed the putt and they will miss vital information that could inform future performances. In accordance to Schmidt's (1975) Schema Theory, information gained via a tracking response helps to develop the recognition schema and also impacts upon the recall schema. Increased exposure to variation-allows enrichment of recognition schema, via online feedback. Tracking the ball post impact is required to ensure information via the recall schema is used to assist the individual to perform the skill, and without this information the transfer of this skill in varied conditions would be limited. During post tracking it is important the individual actively selects the visual target (ball) to engage in pursuit tracking (Spering & Montagnini, 2011). Pursuit tracking is characterised by two main phases, open loop and closed loop (Lisberger et al., 1987). The open loop phase is related to golf putting. In the open loop phase, gaze initially accelerates in the direction of the target, then adjusts to match target velocity. It is predicted that if the individual can track the ball following an effective ball contact this will result in an improvement in performance on a task that emphasises green variations and adaptive response. To explore this further, tracking responses will be measured, to identify whether expert golfers track the ball and if they do track the ball, if they experience a performance benefit. In current research there is a gap in knowledge regarding how a golfer is able to successfully adapt recognition and recall schema.

An alternative approach to perceptual expertise is from an Ecological Dynamics perspective. In this approach there are no cues, and perceptual expertise is underpinned by the cyclical relationship between intention, perception and action (Davids et al., 2012). When an athlete intends to successfully complete a sporting behaviour, they use information in the environment to guide their action. Through experience and the associated success and failure, the athlete learns to refine the emergent behaviour (Davids et al., 2012). From an ecological perspective, gaze/vision enables the individual to view and take notice of the ambient environment (Gibson, 2015). Within real-world golf environments there are specific environmental properties and affordances, including hole position, variation in slopes, time of day and sun exposure to the greens. Examples of pre competition affordances include the golfer having the ability to search the environment during practice rounds or on the practice green. During the competition, example affordances include the option to track their opponents' ball on the same hole and/or their own ball on previous holes in the same round. Taken from an ecological perspective, expertise-based differences could be expected as expert performers are able to use environmental and task related constraints information to achieve optimal movement and consistent performance outcomes (Seifert et al., 2014).

Expertise based differences were found by Seifert *et al.* (2014) who found expert performers have the capability to exploit environmental information and task related constraints in comparison to their less skilled counterparts. In order to perceive information for action an individual needs to be able to 'tune' into this information, via the "*resonance mechanism*" in the central nervous system (Teques et al., 2017, p. 40). Without 'proper tuning' the individual does not resonate with the perceptual information. By studying individuals on a longitudinal basis this information can help predict/track how expertise is developed over time.

2.6 Rationale

Currently QE is at a "critical crossroads" as many questions remain unanswered; particularly related to why QE duration is beneficial for performance (Vickers, 2016). At this stage, cognitive mechanisms are arguably the most widely investigated and reported, with response programming being the most prominent explanation of the function of QE duration (Walters-Symons et al., 2018). It is proposed a longer QE enhances performance due to a longer period for cognitive programming (Vickers, 1996; 2007; Williams et al., 2002) based on the tenants of the location-suppression hypothesis proposed by Vickers (1996). However, the response programming explanation does seem contradictory to what is known about expertise in sport, such as the neural efficiency hypothesis (Del Percio et al., 2009). These concerns are captured by Mann *et al.* (2016)

> *"If efficiency, strictly speaking, enables experts to perform greater, more detailed work in relation to the total energy expended, how then does the QE represent and/or enable efficiency?" (p. 2).*

It is believed examining neural activity may enable insights into the processes underpinning perception and action (Wilson et al., 2016) and provide further knowledge of the behavioural and neural mechanisms of performance-enhancing strategies used by expert performers (Gonzalez et al., 2017). The current 'one size fits all' approach of the

QE optimal recommendations, does not sit comfortably with the known idiosyncrasies of experts in (Dicks et al., 2010). Furthermore, QE duration research is only focused on the final fixation on the back of the ball, thus limiting our knowledge on how perceptual-cognitive expertise features throughout the whole putt routine. An Ecological Dynamics approach to QE and perceptual intervention training may offer an alternative approach here, especially as more recent findings suggest variability in gaze behaviour relative to performance may be task and individual specific (Renshaw et al., 2019). Therefore, the overarching aims of this thesis is to develop a greater understanding of perceptual-cognitive expertise in golf putting and how cognitions, perception and kinematics interact and influence golf putting performance. There are several key questions this thesis will try to address, namely,

1. Can the efficacy of QE for performance be established after further study using a range of task designs, within participant design and individual trial analysis?
2. Is there any specific neural activity associated with successful performance and/or related to the underpinning mechanisms of QE?
3. What are perceptual-cognitive requirements for golf putting when incorporating all stages of a golf putt routine (pre, motor and post)?
4. The feasibility of a perceptual-cognitive intervention to improve putting performance?

The performance led approach used in this thesis enables a range of methodologies to be used throughout this thesis. This will also enable a further aim to be addressed, namely:

5. What theoretical orientation is best suited to exploring perceptual-cognitive expertise in golf putting?.

Chapter 3: Study 1- Examining Quiet Eye using a Representative Task Design with highly skilled golfers

The current chapter details the rationale for, and results of, Study One. The main aim of Study One is to explore the relationship between expertise and Quiet Eye (QE) status in the context of a representative putting task. The task design has been specifically planned to best recreate the demands of a competitive golf environment through a) use of a simulated green surface, and b) use of an experimental paradigm that manipulates task difficulty by varying the slope and distance of the putt. As shown below, observations of golf putting under these conditions raise serious challenges for the view that optimal QE duration as defined by the literature (Vine et al., 2011) is key to successful putting.

3.1 Introduction

Quiet Eye (the final fixation >100ms on the back of the ball; see Vickers, 1992) has been shown to be a robust marker of perceptual-cognitive expertise which can differentiate between highly-skilled and less-skilled performances, even within experts (Wilson et al., 2016). The evidence reported to date within the literature suggests a longer QE duration offers a performance advantage over a shorter QE duration (Wilson et al., 2016). More specifically, in golf putting, a QE duration of 2-3 seconds is considered optimal (Vine et al., 2011). The assumption that a longer QE duration is associated with greater putting performance (Moore et al., 2012) is supported by evidence that reveals experts are able to utilise an effective QE period because they a) initiate the onset of QE before novices, and b) have longer QE durations than novices (Vickers, 2007; Vine et al., 2011). Longer QE duration is proposed to be beneficial because it allows for an extended time for cognitive pre-programming, based on the location-suppression hypothesis (Vickers, 1996, 2007; Williams et al., 2002).

Evidence further supporting a link between longer QE durations and enhanced performance has been provided by Walters-Symons *et al.*(2017) who examined QE duration as a function of trial sequence in golf putting. In this experiment, experienced (single handicap) golfers and novice golfers used a standardised putter to complete 10ft straight putts on a flat artificial green. Participants were told to keep putting until the researcher asked them to stop. Unknown to the participants, they were required to achieve five unsuccessful putts (misses) and five successful putts (hits). On average it took the experienced golfers' fewer putts to achieve the required outcomes than the novices (*M* = 13.72 putts ± 9.88 and *M* = 25.66 ± 10.33 putts respectively). Results revealed that misses (QE duration of *M* = 1389.93ms, *SE* = 90.86) that were followed by putts with a longer QE duration (*M* = 1652.60ms, *SE* = 104.70) led to success (i.e., hits), whereas misses (QE duration of *M* = 1561.56ms, *SE* = 114.34) followed by putts with a shorter QE duration (*M* = 1438.92ms, *SE* = 96.36) led to failure (i.e., misses). The authors concluded that analysing QE duration as a function of trial sequence allows the benefits of longer QE durations to be seen, however, they did not explain why QE duration for misses was sometimes higher than that for hits. From an applied perspective, the finding that QE duration can improve performance and promote error recovery is promising. Walters-Symons *et al.*'s research was, however, conducted using a repetitive straight putt set up, with experienced golfers using an unfamiliar putter. It would therefore be of considerable interest to explore if these findings are also present when putting is examined using a representative task design.

Notably, not all studies examining golf putting support the putative link between QE duration and performance. For example, Panchuk *et al.* (2014), revealed QE duration instruction led to no significant differences in putting accuracy, despite the QE effect being present as the QE instructions had successfully changed gaze behaviour. Similarly, Moore *et al.* (2012) found QE duration did not mediate differences in performance between QE trained and control groups. These findings are consistent with a reflective account of researchers trying to apply QE duration with elite athletes, who found optimal QE duration, as recommended by the current literature, does not always lead to successful performance (Farrow & Panchuk, 2016). Moreover, studies with expert golfers also found golfers can have putting success with QE durations below optimal durations i.e., QE durations < 2 seconds (Campbell et al., 2019; van Lier et al., 2010). In support of shorter QE duration leading to success in comparison to longer QE durations, Mann, Wright and Janelle (2016) have argued it is counterintuitive that experts and expert performance are both characterised by a longer QE period, given that expert performance is synonymous with efficient processing. The mixed success in performance, combined with the lack of understanding of how QE duration improves performance (Gonzalez et al., 2017), is problematic for coaches and practitioners trying to apply QE (Farrow & Panchuk, 2016).

A common thread that links the studies reporting alternative findings (except for

Moore et al., 2012) is the representative nature of the tasks used in the experiments, reflected in a range of task and person specific constraints including: 1) the level of the golfers expertise; 2) the putting surface chosen; 3) the use of a full pre-shot routine before each putt; and 4) participants using their own equipment.

During competitions, at each hole, golfers are required to hit different putts, always from a unique location relative to the hole. In this format, the associated task difficulty varies at each hole and the golfer is required to meet the ever-changing task demands. In the few studies that have attempted to manipulate task difficulty, through length and slope, in golf putting the impact on QE duration is not clear. For example, when increasing task difficulty, by varying putt length [shorter (4ft) and longer (8ft), using a non-representative repetitive putt format], Walters-Symons *et al.* (2018) found QE duration increased with the length of the putt. Alternatively, when task difficulty has been varied through the use of slope, QE duration has not been found to increase (van Lier et al., 2010; Wilson & Pearcy, 2009); instead sloped putts (harder task difficulty) have been shown to produce shorter QE durations than straight putts (easier task difficulty). It is also important to highlight the notion QE duration should increase in line with task difficulty appears to be inherently contradictory to the assumption that a longer QE duration leads to an increase in performance. Regardless, overall, the literature in sports (other than golf putting), does demonstrate QE duration increases with task difficulty (for more information see Lebeau et al., 2016 review). Further research is therefore required to understand how QE duration links to performance in tasks that vary in difficulty.

Given that the evidence supporting the assumptions behind QE theory comes from studies using non-representative tasks, a key aim of the current study is to examine QE in the context of more realistic putting (i.e., using a representative task design, *cf*. Brunswik, 1956). The importance of examining golf putting performance using a representative task design was highlighted by the literature reviewed in Chapter 2. Demonstrating the effects of QE in more ecologically valid naturalistic putting environment is important, at least in part because it means the results can be more easily translated into changes in practice for golfers, coaches and practitioners.

The current study aims to observe behaviour and QE duration in high skilled golfers, to assess the impact of QE duration on performance, including how QE duration varies as a function of task difficulty. The representative task includes both sloped and straight putts, from four distances (3ft, 8ft, 15ft, and 25ft). The task has been specifically designed to include a range of difficulty and highly skilled participants are examined to provide evidence as to whether the current QE assumptions hold true in a representative task design (Brunswik, 1956). Based on the existing QE literature it is hypothesised i) a longer QE duration will lead to significantly enhanced performance in comparison to a shorter QE duration, and ii) there will be an increase in QE duration as a function of task difficulty (i.e., comparing sloped putts versus straight putts, and long putts versus short putts).

For this study, to extend current research, in addition to measuring QE on the ball (the standard QE period measured in golf putting) a viewing duration will also be measured on the hole (hole: last fixation on the hole 1◦ degree visual angle >100ms) and during the post-shot period (known as QE Dwell). Research has indicated the potential importance of the time spent fixating on the far target (i.e., the hole in golf putting) as well as the near target (i.e., the ball in golf putting; Moore et al., 2012; Vickers, 2007; Vine & Wilson, 2010). At present, however, there is no guidance on what duration of time should be spent looking at the hole in golf putting. Consistent with the benefits of a longer QE on the ball, evidence suggests a longer QE Dwell duration (gaze focused on the green after hitting the ball for a minimum of 200ms, has been linked to an improvement in performance in comparison to a shorter QE Dwell (Vine et al., 2013). In the current study, therefore, we hypothesise that a viewing time on the hole followed by QE on the ball and QE Dwell should be more effective for performance than just a QE duration on the ball, or hole, or QE Dwell, alone.

3.2 Methods

3.2.1 Research Design/Methodology

A single repeated measures experimental design was used. Participants’ putting performance, eye-movement and kinematics were measured whilst carrying out a series of putts on an indoor artificial surface. Critically the surface had a stimp value of 10.2 stimp (a measure of green speed, whereby the higher the stimp rating the faster the green). A stimp rating of 10.2 is comparable with real-world green speeds that occur during competition with elite golfers.

3.2.2 Participants

Participants were twenty-two experienced golfers (18 males and 4 females), with a mean age of 31.3 years ± 15.7, including 15 amateurs (handicaps ranging from -2 to +5, with a mean handicap of 1.98 ± 0.04) and 7 professionals. All participants were right-handed, right eye dominant, and had normal or corrected-to-normal vision. Ethical approval was granted by the College of Health and Life Science Research Ethical Committee which is overseen by the University Research Ethics Committee (UREC) at Brunel University. All procedures were in accordance with the Declaration of Helsinki ethical principles for conducting research with human participants. The lead researcher contacted the performance director from a National Governing Body for permission to speak to players matching the eligibility criteria. The lead researcher then met interested players to explain the study requirements and related information. Following this meeting, players were asked to confirm their involvement in the study by sending the lead researcher a signed copy of the informed consent sheet along with their demographic information. The players were made aware that participation was not a requirement, that it was voluntary without obligation, and that participation had no influence on training and selection.

3.2.3 Procedures

Participants were required to attend one two-hour testing session (Figure 2) with specific details outlined in the procedures below.

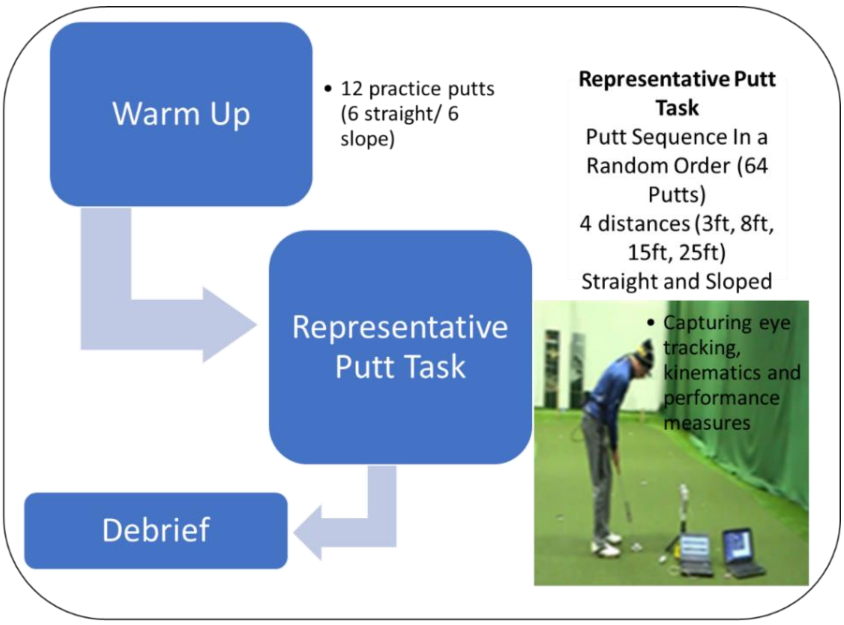


Figure 2. Schematic of the testing protocol, including an image of testing in action, showing a participant who is wearing the eye tracker and has SAM PuttLab triplet fitted to his putter in the indoor putting environment.

Eye Tracker Fitting and Calibration

An ASL mobile eye tracker (XG Mobile Eye Tracker, Applied Science Laboratories, Waltham, MA) was fitted to the participant by the researcher, consistent with previous research (Wilson & Pearcy, 2009, Vine & Wilson, 2010). The eye tracker was calibrated using five coloured markers positioned near the participant's feet when standing in putting posture and addressing a golf ball (see Figure 3). During calibration participants were asked to adopt a normal putting stance and to hold their vision steady on the centre of each marker, in a pre-designated order, for a duration of 100-200ms. During the calibration process, participants used their own putter (that had been fitted by a golf professional prior to the study, to ensure consistency for all participants) and Srixon AD333 Tour golf balls (consistent with the protocol for the rest of the testing session).

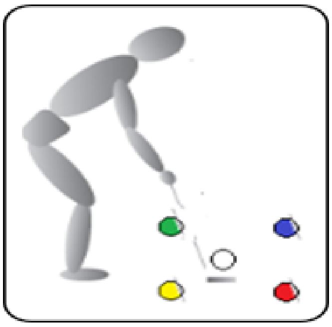


Figure 3. Illustration of ASL calibration procedure(adapted from van Lier, 2011).

Warm Up

Participants were given an opportunity to ask questions prior to commencing the experiment and asked not to discuss the experiment following the session. Participants completed a standardised warm up involving 12 practice putts (6 straight/6 sloped) to different putt locations, and holes used in the representative task.

Representative Task Design

Following the warmup, participants completed a representative putting task on the same indoor artificial surface. Task difficulty was manipulated by varying the distance (3ft, 8ft, 15ft, and 25ft) and condition/lateral slope of the putt (slope, no slope). The order in which the putts were taken was unique for each golfer, generated using a nested design whereby a) putt distance was randomised across participants, with the constraint that distance did not increase or decrease linearly (i.e., 3, 8, 15, 25 and 25, 15, 8, 3), and then within each distance, b) putt type was randomised (see Figure 2). Participants were given forty seconds to complete each putt and asked to carry out their normal putting routines. The total testing time ranged from 1.5 - 2 hours.

Debrief

After all putting was completed, participants were given a chance to ask any questions and reminded about their ability to withdraw. Participants were also given the researcher's contact details to give the participant a chance to ask any questions in the future.

3.2.4 Measures captured during the representative task

3.2.4.1 Visual Search Behaviours

Visual search behaviours were captured using ASL XG Mobile Eye Tracker, consisting of mobile eye tracker lenses and EyeVision software (ASL Results Pro Analysis, Argus formally, ASL) installed on a laptop (Dell Inspiron 6400). Consistent with previous research (Vine et al., 2013; Vine et al., 2011) gaze location is represented by a crosshair cursor (representing 1° of visual angle) in a video image of the scene (spatial accuracy of ± 0.5° visual angle; 0.1° precision; see Figure 4). All analysis was completed post testing. QE durations were calculated using ASL Results Pro (ASL Results Pro Analysis, Argus formally, ASL).

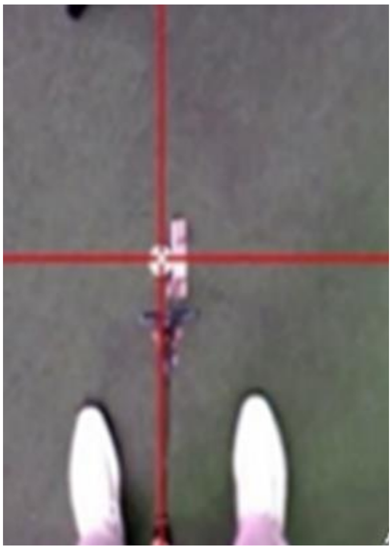


Figure 4. Screenshot illustrating the identification of a fixation on the golf ball, as recorded by the ASL eye tracker.

As illustrated in Figure 5, in the present study vision was measured on the hole, QE, QE Dwell. Measures included 'Viewing time on the Hole' –fixation on the hole 1◦ degree visual angle >100ms prior to initiation or QE duration. was measured at three stages: a), b) QE (QE-early)- a minimum of 100ms starting at QE onset and ended with the initiation of the backswing with less than 1 degree of visual angle (Vine et al., 2015).

and c) QE Dwell – a minimum of 200ms with the eyes focused on the green after hitting the ball (Vine, Lee, Walters-Symons, & Wilson, 2015). For QE ball, fixations that were too short were coded as No QE. All putts were categorised according to the presence of gaze strategy (i.e., Hole only, QE Ball; Hole and QE Ball and QE Dwell, etc.).

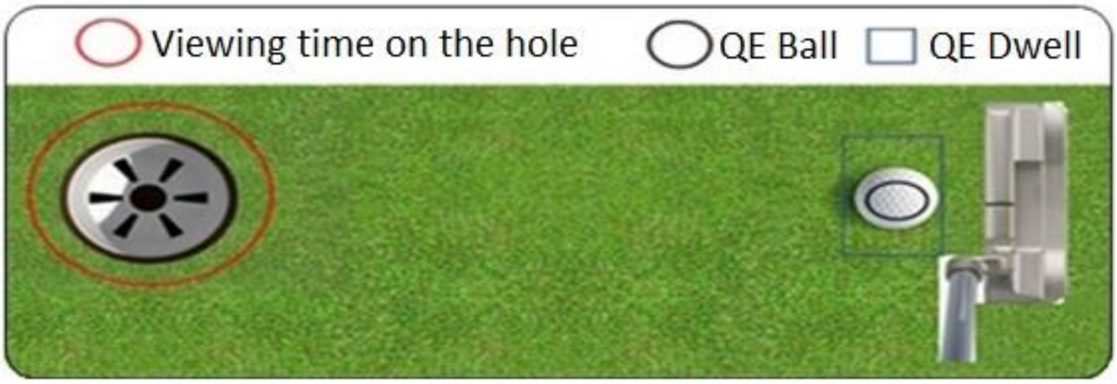


Figure 5. Visual representation of measured gaze strategies, illustrating the different stages of putting during which gaze behaviour was assessed, namely on the hole, QE on the ball and QE Dwell post putt.

3.4.2.3 Movement Phase Durations

The phases of the putting action: preparation, backswing, forward swing and post contract tracking were calculated using Quiet Eye Solutions software (Quiet Eye Solutions Inc., Calgary, CA). Preparation, backswing and forwardswing movement phases are consistent with previous research (Vine et al., 2013).

3.4.2.4 Performance

Performance was assessed through the number of successful putts. Putting error was measured by calculating absolute distance from the hole (cm) and angle from the hole (degrees). These values were calculated manually using Kinovea (Version 0.8.12, https://www.kinovea.org /) from photographs of each trial, off-line, after testing was completed. Photographs were taken from a camera on a fixed stand which allowed the picture to be taken from directly above the hole. The stand was placed in the same position at each hole for consistency.

3.4.2.5 Swing Kinematics

Impact spot consistency was captured by SAM PuttLab (Version 5, Science & Motion Sports). Impact spot is defined as the exact place the ball hits on the putter face. Impact spot consistency highlights the variability in point of impact, with 100% being no variability and 0% being high variability. Following SAM PuttLab instructions, a SAM PuttLab triplet was fitted to the participant's putter, and was calibrated before every block of four strokes, with the putter flat and square to the target.

3.2.5 Statistical Analysis on the representative task

To establish the overall pattern of putting performance, putting success rates (% putts holed) were analysed using repeated measures ANOVA, revealing whether there were any differences in performance as a function of putt distance and/or slope. A further, one-way ANOVA was conducted to explore if performance (% putts holed) was associated with expertise (higher and lesser skilled, based on median split of the average putts per round data). For all analyses significance was accepted at $p < 0.05$; all data are presented using means and ± *95%* CI, and a Greenhouse Geisser correction for non-sphericity was applied where the data violated assumptions of the ANOVA.

To explore the pattern of behaviour in more detail performance was also assessed by examining mean error locations [i.e., the distance (in cms) using a repeated measures ANOVA in SPSS and direction (in degrees) from the hole on missed putts] using a circular statistics toolbox in MATLAB (Berens, 2009). Circular statistics (Berens, 2009) calculates the mean resultant vector, resultant vector length (R Length) and variance (bounded in the interval [0, 1]). If all error locations are in the same direction, the resultant vector will have a length close to 1, and the circular variance will be small. If the error locations are spread out evenly around the circle, the resultant vector will have a length close to 0 and the circular variance will be close to maximal. The Raleigh Test explores how large the R Length must be to indicate a non-uniform distribution (Fisher, 1995), where a small *p* indicates a significant departure from uniformity and indicates to reject the null hypothesis (Berens, 2009). An additional experimental analysis (Appendix 1) using the circular statistics toolbox was used that transforms cartesian coordinates (reflecting the position of the ball relative to the hole) into two dimensional vectors (coding distance and direction), allowing the mean distance and direction to be calculated. Error data were initially generated separately for each putt, and then a mean distribution of errors around the hole was calculated in successive 10-degree bins (averaged across all misses within each bin). A median split based on average putts per round was used to separate the participants into two groups: lower (< 30 putts) and higher (> 30 putts). To explore between group differences, Watson-Williams tests were conducted.

To explore if QE duration is linked to performance six sets of statistical tests were completed examining the relationship between putting success rates and QE. The first analysis reflects a subset of the original performance data (e.g., due to loss of trials on which fixation could not be identified) this analysis only included factors that were significant in the initial analysis of performance, and only outcomes involving QE are reported. Analysis of QE data employed a repeated measures ANOVA to examine putting success rates as a function of QE duration, separating the QE data into a series of successive time bins (details of time bins and ANOVA structure provided in the relevant results section). The second analysis was conducted to replicate existing analysis in the literature, examining mean QE as a function of hits and misses.

In the third analysis, data was explored to examine whether an increase in QE duration from the previous trial to the subsequent trial influenced the outcome of the putt. Data is presented at a group level, allowing paired *t*-tests to be conducted on success rates.

For the fourth analysis, a median split based on QE duration was used to separate the participants into two groups: lower than average and higher than average QE duration to examine mean error locations [i.e., the distance (in cms) using a repeated measures ANOVA in SPSS and direction (in degrees) from the hole on missed putts] using a circular statistics toolbox in MATLAB (Berens, 2009). Also, an additional experimental analysis (Appendix 1) using the circular statistics toolbox was used that transforms cartesian coordinates (reflecting the position of the ball relative to the hole) into two dimensional vectors (coding distance and direction), allowing the mean distance and direction to be calculated was also completed to compare the two groups (lesser and higher than average QE duration). To explore between groups, Watson-Williams tests were conducted to assess whether the mean directions were statistically different.

The fifth analysis was conducted to replicate existing analysis in the literature, using a paired *t*-test to assess if there are any differences in impact spot consistency in relation to QE Dwell duration (compared to No QE Dwell). Finally, to explore if there are any differences in putting success as a function of the visual strategy adopted, performance was examined using an ANOVAto compare performance across the six different patterns that were observed: hole only, QE Ball only and QE Dwell only; hole + QE ball, QE ball + QE Dwell, and hole + QE Ball + QE Dwell. One other visual strategy is possible (hole + QE Dwell) but did not occur in any putt.

3.3 Results

3.3.1 Does manipulating task difficulty impact on performance?

Putting success rates were measured during a representative putting task, whilst task difficulty was manipulated. The data are illustrated in Figure 6, revealing a wide range of variability: from 98% success for 3ft straight putts to 11% for 25ft sloped putts. The data were analysed using repeated measures ANOVA with the factors of putt distance (4: 3ft, 8ft, 15ft, 25ft) and putt type (2: straight/slope), revealing robust differences in performance as a function of putt distance ($F_{(3,63)} = 176.554$, $p < 0.001$, $\eta^2 = .894$), reflecting increased success at shorter putt distances, and putt type ($F_{(3,21)} = 59.585$, $p < 0.001$, $\eta^2 = .739$), reflecting increased success for straight compared to sloped putts. In addition, and consistent with the impression provided by Figure 6, the analysis also revealed a significant interaction between putt distance and putt type, ($F_{(3,63)} = 3.193$, $p = 0.029$, $\eta^2 = .132$), reflecting the type of putt (straight versus sloped) did not influence performance on shorter putts, but pronounced differences were exhibited as putt distance increased.

An additional follow-up analysis was carried out to check whether the direction of sloped putts (L to R versus R to L) influenced putting performance. The direction was manipulated to ensure the task was engaging and varied, rather than as a manipulation of difficulty, and putting success rates were markedly similar across the two directions (LR = 39%; RL = 41%). A paired samples *t*-test confirms there was no significant difference ($p = 0.5$) in total hits between the two types of slope; consequently, the direction of slope is not included as a factor in any further analysis.

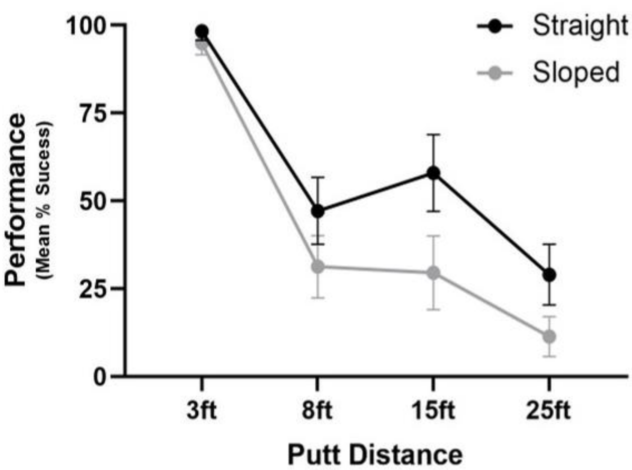


Figure 6. Performance (mean % success and 95% CI), shown as a function of distance and slope (straight = black and slope = grey line). Performance is affected by changes in distance, but the effect of putt type is only evident for longer putts.

3.3.2 Is performance related to skill level?

To assess golfing performance, we measured success rates during the representative putting task, as a function of skill level. A median split based on average putts per round was used to separate the participants into two groups: lesser (< 30 putts) and higher (> 30 putts). Performance on the representative task (64 putts) was similar between higher skilled golfers (*M* = 44% ± 8.72) and lesser skilled golfers (*M* = 49% ± 4.6). This data was analysed using a one way between groups ANOVA to explore whether skill level was linked to performance (total % success). The analysis revealed the difference in performance between the two groups was not statistically significant ($F_{(1,20)} = 3.124$, $p = 0.92$): performance did not vary as a function of skill level.

3.3.3 Does error location change as a function of skill level?

The next set of analyses focused on characterising the distribution of missed putts. The final position of each missed putt was recorded, and the location data (angle and distance) were examined as a function of skill level (based on a median split of average putts per round). Figure 7 and Table 6, present data, representing the distribution of angle error around the hole. The R Length decreases as the putt distance increases and the variance increases, highlighting the spread of errors is related to putt distance.

Table 6. Properties of angular data for missed putts, representing central tendency and spread as a function of putt distance (8/15/25ft) and skill level.

	Putt Distance (ft)	*Mean Resultant Vector (°)*	*R Length (0,1)*	*Variance (0,1)*	*SD*	*Raleigh Test of Uniformity (p = < 0.05)*
Lower Skill	8	176	0.57	0.43	0.92	<0.001
	15	154.46	0.18	0.82	1.28	<0.02
	25	145	0.16	0.84	1.30	<0.02
Higher Skill	8	178.21	0.64	0.36	0.85	< 0.001
	15	163.87	0.41	0.59	1.09	<0.001
	25	163	0.22	0.78	1.25	<0.001

To assess if there were any differences in angle location a Watson-Williams test was used to compare the distribution of errors around the hole as a function of skill level (higher and lower skilled golfers). At 8ft there was no difference in error location between the two groups ($F_{(1,215)} = 0.08$, $p = .783$). Equivalent analysis for 15ft putts revealed there was not a statistically reliable difference in the distribution of errors between the two groups ($F_{(1,228)} = 0.44$, $p = 0.506$). Critically at 25ft, analysis revealed there was a difference in error location ($F_{(1,300)} = 3.91$, $p = 0.04$) between the two groups with the higher skilled group displaying less variance in their error location.

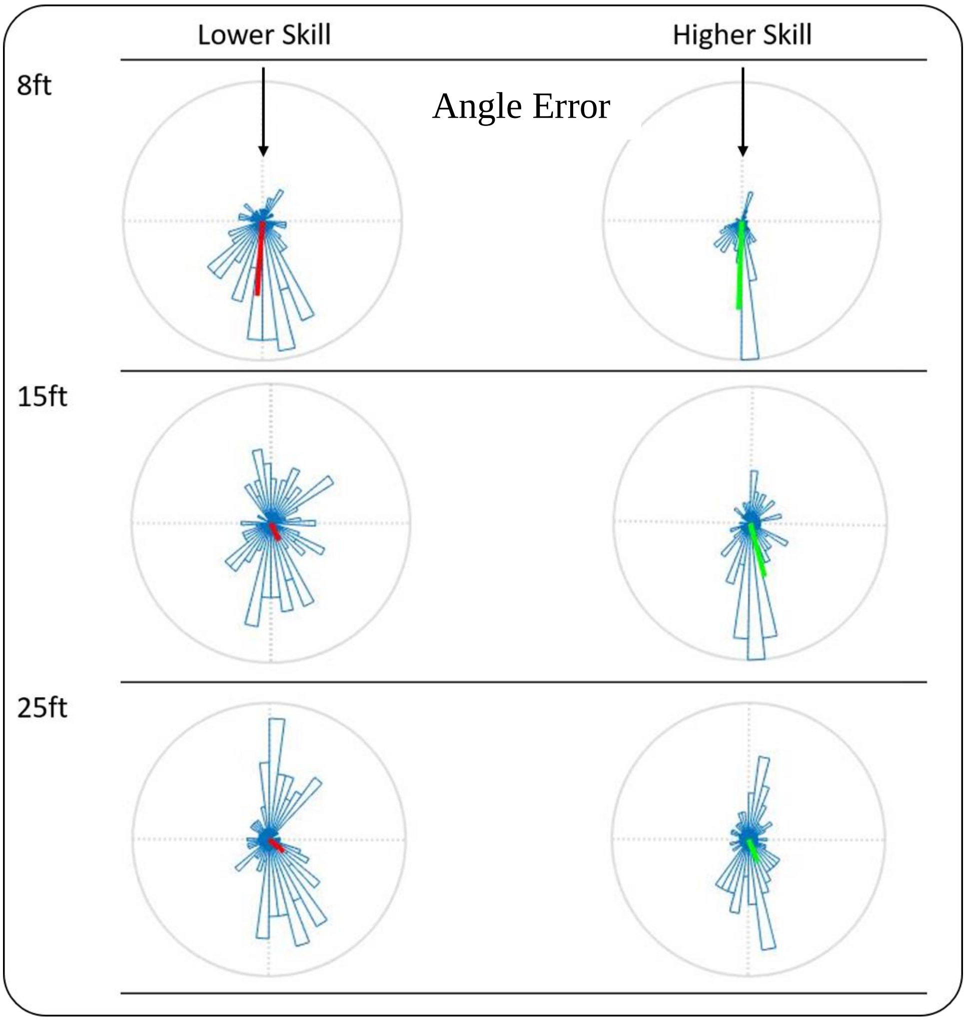


Figure 7. Angle histograms to represent the distribution of angle location in the missed putts (with the centre of the graph representing the hole, the two grey dotted lines separating a short/long miss and miss left/right of centre, the outer ring represents the largest mean angle error for that data set). The arrow indicates the direction of the ball from the putter. Each plot represents the distribution of missed putts around the hole, shown separately as a function of putt distance (8ft, 15ft, 25ft) and skill level (lower/higher median split based on average putts per round). The blue lines represent the frequency of errors around the hole. The red lines indicate the direction and magnitude of the mean resultant vector for lower skilled and the green lines indicate the direction and magnitude of the mean resultant vector for the higher skilled.

In addition, error was also explored in terms of distance (cm) away from the hole. A mixed within- and between-participants repeated measures ANOVA was conducted to see if the putt distance (8/15/25ft) error varied based on skill level (higher or lower based on the median split of average putts per round). Mean scores indicated errors increased in line with putt distance, with greater error lengths recorded for the longest putt distance: 8ft (higher 25.98cm ± 9.59; lower 23.11cm ± 7.51); 15ft (higher 22.07cm ± 9.93; lower 25.04cm ± 9.89) and 25ft (higher 39.98cm ± 14.04; lower 46.11cm ± 14.57). Analysis revealed only one significant result, a main effect of putt distance [$F_{(2,19)}$ = 21.75, p = <0.001, η^2 = .696]. Post hoc pairwise comparisons revealed errors were significantly larger for 25ft than 8ft putts [mean difference = 18.701, SE = 3.301, $p < 0.001$] and 25ft in comparison to 15ft [mean difference = 19.177, SE = 2.956, $p < 0.001$], but did not differ between 8ft and 15ft putts.

3.3.4 Does a longer QE duration lead to increased performance?

To explore the relationship between QE and performance, putting success rates were examined as a function of QE duration. A series of QE time bins were formed, including No QE (<100ms), six successive time windows and a maximum QE (>3000ms). The choice of time bin was designed to allow changes in putting success to be revealed, with the traditional recommended optimal QE duration being between 2000 and 3000ms. These data were analysed using ANOVA with factors of QE duration (8: <100ms; 100-500ms; 500-1000ms; 1000-1500ms; 1500-2000ms; 2000-2500ms; 2500-3000ms; >3000ms), putt distance (4: 3ft/8ft/15ft/25ft) and putt type (2: straight/sloped).

Analysis revealed a significant main effect for QE duration ($F_{(5,100)}$ = 14.212, $p < 0.01$, η^2 = .515), reflecting the fact performance varied as a function of QE. Importantly, however, an interaction between putt distance and QE duration ($F_{(15,300)}$ = 2.032, p = 0.01, η^2 = .151) reveals the effect of QE varied between shorter and longer putts. Analysis did not provide clear evidence for a significant interaction between putting type and QE duration ($F_{(5,100)}$ = 2.117, p = 0.06, η^2 = .111), or for a three-way interaction between putt distance, putt type and QE duration ($F_{(15,300)}$ = 0.893, p = 0.57, η^2 = .048), consequently data are collapsed across putt type in Figure 8, which illustrates the effects of QE duration on putting success.

As expected, performance improves from No QE to QE. Contrary to expectations, however, putting success rates are consistently higher at shorter QE, with very low levels of putting success at longer (so-called ‘optimal’ QE) durations. The data exhibits a clear profile of success, with the highest level of performance occurring at the shortest QE duration (100-500ms), except for on 15ft putts, where performance was highest at a slightly longer QE duration (500-1000ms). Overall, analysis suggests No QE led to more successful putts than a QE duration of >1500ms, a shorter QE duration led to better performance than a longer QE durations, and ‘optimal’ QE durations were neither common, nor successful.

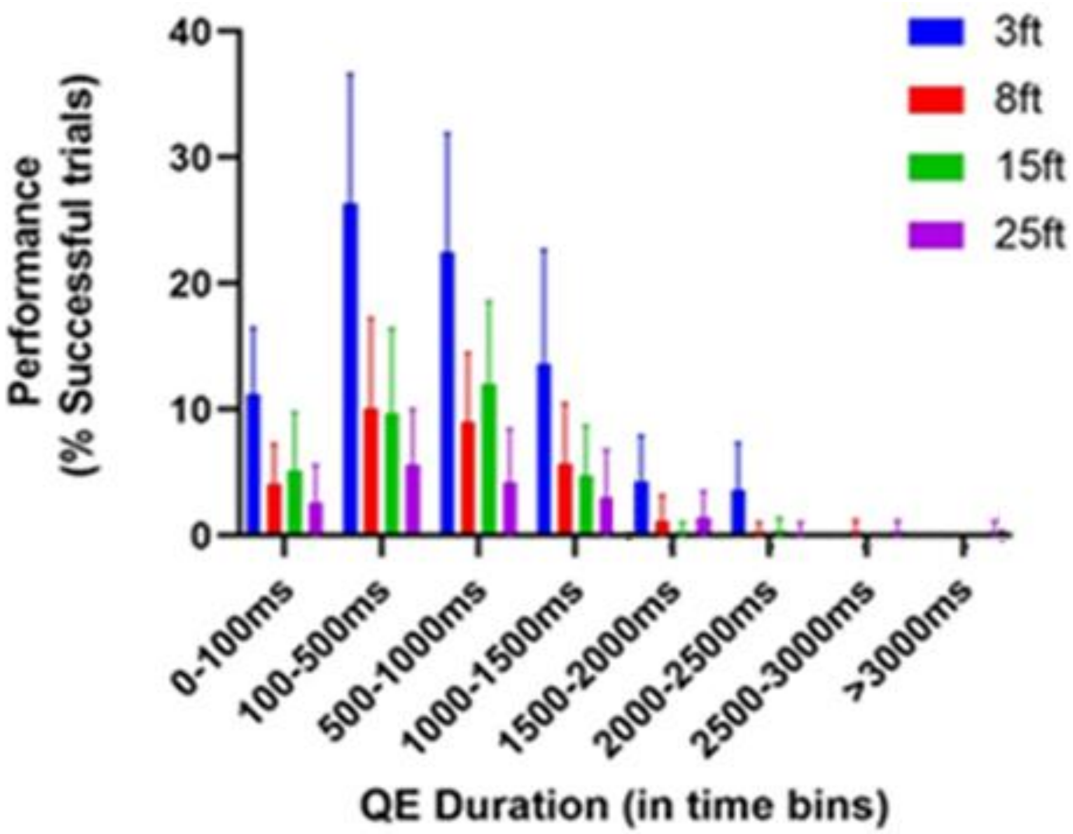


Figure 8. The relationship between putting success (mean % putts holed, 95% CI) and QE duration (in successive time bins), separated by putt distance. Putting success rates vary with putt distance, and there is not an increase in QE as a function of QE.

3.3.5 QE duration and outcome for each participant?

Having demonstrated that putting success rates exhibited a distinct profile as a function of QE duration and putt distance, the following analysis examines QE in a quite different way, replicating analysis within the wider literature. Mean QE duration was calculated (collapsed across putt distance and type) within participants as a function of putting performance (hits versus misses) to examine whether QE duration was longer for successful putts on an individual level. As can be seen in Figure 9 (Panel A) the mean QE duration did not differ as a function of performance outcome, consistent with the results of a paired sample t-test [t(44) = -0.165, p = 0.43]. The variability in mean QE duration across participants is also clearly visible in Figure 9 (Panel B), with 11 participants exhibiting longer mean QE in hits than misses, and 11 participants exhibiting the opposite pattern.

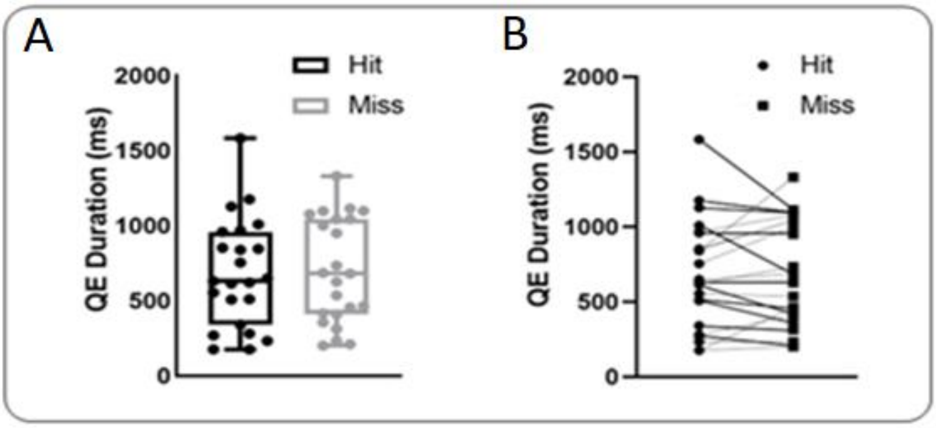


Figure 9. Performance outcome and mean QE duration. ***Panel A represents the mean (and 95% CI) QE for hit and miss putts, revealing a similar mean QE duration regardless of outcome. Panel B highlights the difference between QE duration for hit and miss putts for each individual participant. The dashed lines represent individuals' exhibiting a QE duration that was higher for misses than hits, whereas solid lines represent the opposite pattern.***

3.3.6 Do increases in QE duration influence performance?

To examine if an increase in QE duration from the previous trial to the subsequent trial influenced performance, the data was explored on a trial-by-trial basis, examining sequence effects. For this analysis the 3ft putts were excluded due to there not being enough misses at this distance. Initial inspection of the data suggested that there was no clear pattern relating changes in QE duration to putting success, so the data were collapsed across putt distance and type. For example, on two occasions (in two participants) the same increase in QE duration led to both a hit and miss (at the same putt distance and putt type). Similarly, across all putts the greatest increase in QE duration that led to a hit was 2280ms and the smallest that led to a hit was 30ms, and for misses the greatest increase in QE duration was 2670ms and the smallest was 30ms. Assessment of sequential changes in QE revealed that when the preceding trial was a hit, putts associated with increases and decreases in QE exhibited similar putting success rates (40.39% ± 26.33 and 47.75% ± 41.29 respectively). Moreover, a similar pattern was present when the preceding trial was a miss (leading to success rates of 15.51% ± 9.35 and 22.95% ± 21.62 for increases and decreases in QE respectively). Assessment of performance across participants using paired *t*-tests confirms that there was no significant difference in putting success rates as a function of whether QE duration increased or decreased from the preceding trial ($p > 0.05$). Taken together, these data suggest that putting success rates are not dependent on putt-to-putt changes in QE duration.

3.3.7 Does QE duration influence error location?

The error location data (vectors representing the distance and direction from the hole) were examined as a function of QE duration (two groups of participants, with lower or higher than average QE, based on a median split) to examine whether QE duration influenced the pattern of errors. For these analyses data from 3ft putts was excluded because there were so few misses. These data were also collapsed across putt type because the initial analysis of QE data (see section 3.3.4) revealed no significant differences involving this factor. Figure 10 and Table 7, present data, representing the distribution of angle error around the hole using circular statistics toolbox (Berens, 2009). As the putt length increases the R Length decreases and the variance increases with the largest spread of errors occurring at 25ft putt distance.

Table 7. Properties of angular data for missed putts , representing central tendency and spread as a function of putt distance (8/15/25ft) and QE duration.

	Putt Distance (ft)	*Mean Resultant Vector (°)*	*R Length (0,1)*	*Variance (0,1)*	*SD*	*Raleigh Test of Uniformity (p = < 0.05)*
	8	174.37	0.52	0.48	0.98	<0.001
Lower QE	15	174.24	0.31	0.69	1.18	<0.001
	25	159.19	0.20	0.80	1.26	<0.001
	8	177.75	0.66	0.34	0.82	< 0.001
Higher QE	15	170.96	0.28	0.72	1.20	<0.001
	25	135.04	0.14	0.14	0.86	0.06

To assess if there were any differences in angle location a Watson-Williams test was used to compare the distribution of errors around the hole as a function of QE duration (lower than average and higher than average). Across the three putt distances there were no significant differences in the distribution of errors between the two groups (8ft: $F_{(1,204)} = 0.86$, $p = 0.354$; 15ft: $F_{(1,213)} = 1.18$, $p = 0.278$; 25ft: $F_{(1,273)} = 2.55$, $p < 0.111$), meaning error location did not change as a function of QE duration.

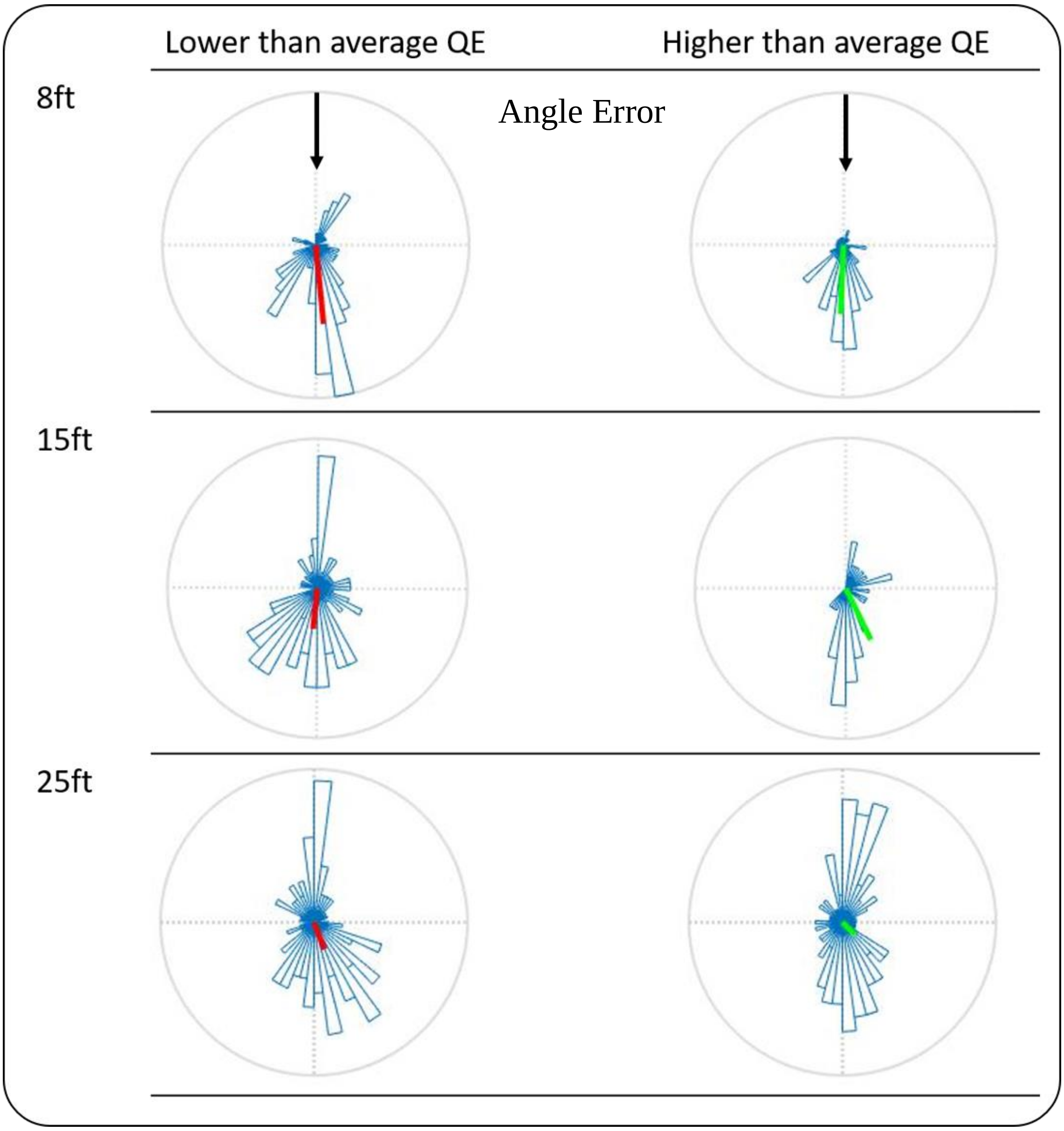


Figure 10. Angle histograms to represent the distribution of angle location in the missed putts (with the centre of the graph representing the hole, and the outer ring representing the largest mean angle error for that data set). The arrow indicates the direction of the ball from the putter. Each plot represents the distribution of missed putts around the hole, shown separately as a function of putt distance (8ft, 15ft, 25ft) and QE duration (lower/higher than average based on median split of QE duration). The blue lines represent the frequency of errors around the hole. The red lines indicate the direction and magnitude of the mean resultant vector for lower skilled and the green lines indicate the direction and magnitude of the mean resultant vector for the higher skilled.

Distance error data, revealing variability in how far away misses were from the hole (cm) were analysed using mixed ANOVA with a between subjects factor of QE duration (2: higher/lower average QE) and a within subjects factor of putt distance (3: 8ft/15ft/25ft). Analysis revealed a main effect of distance [$F_{(2,17)} = 19.736$, $p < 0.001$, η

^{2}= .699], reflecting that misses ended up further away from the hole as the length of the putt increased. A significant interaction between distance and QE duration [$F_{(2,17)}$ = 4.217, $p < 0.033$, η^{2} .332] reveals there were differences in how QE duration influenced distance error across the putts. Missed putts were further away from the hole at 8ft and 25ft (8ft higher QE: 29.76cm ± 7.39cm and 25ft higher QE: 45.05cm ± 11.42cm respectively) for golfers exhibiting an higher QE duration, in comparison to golfers exhibiting a lower QE duration (8ft lower QE: 20.24cm ± 7.28cm and 25ft lower QE: 41.26cm ± 16.88cm respectively). In contrast, the reverse was true at 15ft: misses were 26.35cm ± 10.59cm away from the hole in participants with lower QE, compared to 21.86cm ± 10.38cm away for participants with a higher QE. Taken together the findings suggest QE duration does not impact on the location of error in terms of angle but does impact the location relative to the distance away from the hole change, with longer QE durations not always leading to a shorter miss in distance (cm) away from the hole.

3.3.8 Does QE Dwell duration influence putting kinematics?

Examination of putting success rates revealed no differences based on whether the participant had a QE Dwell period (M = 83.07) or QE Dwell was absent (M = 83.55), a result that was confirmed using a paired samples *t*-test [$t_{(22)}$= 0.069, p = 0.945].

3.3.9 Does visual strategy impact on performance?

To explore the impact visual strategies had on putting success all successful putts were categorised according to the visual strategy employed (based on coding of the eye-movement data). Figure 11 illustrates the proportion of successful putts associated with each visual strategy, with a one-way ANOVA revealing successful puts were associated with specific visual strategies ($F_{(5,138)}$ = 116.8, $p < 0.0001$). Post hoc *t*-tests (Bonferroni adjusted) revealed the visual strategies that were most successful were hole + QE ball and Hole + QE Ball + QE Dwell (see Figure 11), highlighting the importance of looking at both the hole and ball prior to performing.

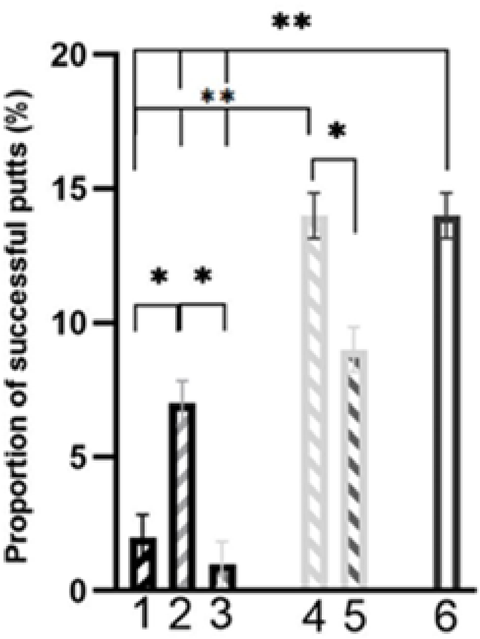


*Figure 11. The impact of visual strategies on performance (1:Hole, 2:QE Ball, 3:QE Dwell, 4:Hole + Ball, 5:QE Ball + QE Dwell, 6:Hole + QE Ball + QE Dwell) implemented by participants on the representative task design and the impact of the strategy on mean putting performance (±95% CI). Post hoc Tukey tests revealed that there were significant differences displayed on the graph ** = p < 0.0001, * p < 0.002.*

3.4 Discussion

This current study aimed to capture the gaze behaviour of highly skilled golfers *in-situ* using a representative task design to assess whether QE duration (early) was linked to performance. One of the main aims was to examine the assumption that a longer QE duration improves performance and early QE duration increases with task difficulty. Contrary to our expectations, this assumption was not supported by the findings; the highest levels of putting success were associated with a QE duration < 1000ms. Notably, performance (% success rates) for QE putts (> 100ms) were higher than No QE (<100ms), however, there was also an increase in performance for putts with No QE duration in comparison to putts with a QE duration of greater than 1500ms. The present findings demonstrate that a longer QE duration does not lead to increased success when putting in the context of a representative task. In support of our findings, Panchuk *et al.* (2014) observed longer QE duration did not always lead to an increase in performance. Taken together, these findings add to the growing evidence that the relationship between QE duration and performance is not as simple as once thought. When using a representative task design, our findings also revealed that QE duration did not differ as a function of task difficulty, despite performance levels changing in accordance with task difficulty (i.e., increased success for the straight putts at shorter distances). Our findings are consistent with previous golf putting data that suggests QE durations are not mediated by task difficulty (Wilson & Pearcy, 2009; van Lier et al., 2011). Although it has been shown that QE duration does vary in line with task difficulty in other target sports (e.g., see Klostermann et al., 2014, Williams et al., 2002) these findings suggest that whether QE duration varies as a function of task difficulty may be task dependent.

To aid the accurate dissemination into applied practice, here in this current study, QE duration findings were analysed on a trial-by-trial basis. Within the wider literature, QE studies typically compare the average QE duration for successful and unsuccessful putts and/or examine performance based on an increase or decrease in QE duration from the preceding trial. When replicating these analyses, contrary to the existing literature, our findings suggest there are no differences in mean QE duration as a function of outcome. Moreover, the data revealed there were no differences in success rates based on an increase or decrease in QE duration in the trial preceding a hit or a miss. Therefore, our findings suggest QE duration may be dependent on the task design and, perhaps more concerningly, not all of our QE findings could be explained through current QE theory.

Our findings raise important questions surrounding the theoretical underpinnings of QE duration - they are not consistent with the location-suppression hypothesis proposed by Vickers (1996). The location-suppression hypothesis is the most widely reported explanation of why QE is beneficial for performance (Walter-Symonds et al., 2017). Based on the tenets of the location-suppression hypothesis, longer QE duration is believed to provide more time to fine tune the parameters of the motor action (such as force, direction, and velocity), facilitating the pre-programming of the action (Williams et al., 2002). However, based on the present results we propose that cognitive processing occurs differently using a representative task in comparison to a repetitive putt design. In a representative task, the problem solving, and processing element of the putt may occur when the golfer is scanning the green and making their decision on the putt strategy, with less processing occurring over the ball. This view receives support from wider evidence that during repetitive putting there is limited scanning of the green, due to the participant not moving their feet and also less requirement to do so because the target is the same (van Lier et al., 2011). Furthermore, in a representative task design different feedback is available as the participant does not typically have direct feedback from their previous trial, so the fine tuning of the motor response will be different. Given the present findings it is critical that further research continues to utilise a representative task design (Brunswik, 1956) to ensure the visual information is consistent to the competitive environment: without this we cannot understand how the golfer is using the visual information in the environment to guide their response (Milner & Goodale, 2008).

The dominance of QE research within golf putting has led researchers to mainly focus on the impact of viewing fixations on the back of the ball (Mann et al., 2007; Vickers, 2007). Our analysis of visual strategies suggests future research should extend the current focus of QE on the ball, to consider the impact of visual strategies on the hole in addition to QE on the ball. We found the visual strategies involving both on the hole and QE on the ball (i.e., viewing time on the hole + ball and QE on the hole + ball + Dwell) were more successful than when QE was on the ball alone. The enhanced performance for QE on the hole and ball demonstrates performance improves when the visual strategies used by golfers reflect both near and far aspects of the aiming task of golf putting. Success of the hole + QE ball visual strategy also supports the notion of a functional linkage between visual and motor systems (Shiffrar & Pinto, 2002). In broader terms, the present findings therefore provide support for an ecological approach to the task, in which the purpose of vision is to view and take notice of the ambient environment and, as a result, each gaze is considered important for performance (Gibson, 2015).

Ecologically, how the individual learns to use these perceptual variables and adapt and refine their movement accordingly can explain differences in successful and unsuccessful performance (Araújo & Kirlik, 2008). Therefore, from an applied perspective it is crucial to gain understanding of how the individual is acquiring perceptual variables via their vision, and how they use the perceptual variables to adapt movement to achieve success. Clearly, golf research that only focuses on QE on the ball (and what is happening in the gaze in the final seconds prior to the initiation of the putter) changes the nature of the putting task to only represents the near aspect of the visual strategy. Importantly, repetitive putting is also distinctly different to competitive golf, where the characteristics of the putt continually change. This change in task demands may account for why studies that have increased the representative nature of the task reveal differences in the impact of QE on performance in comparison to a repetitive task design. As far as we are aware, studies employing repetitive task design (whereby the participants repeatedly hit the same putt), and- the far element of visual strategy (gaze on the target/hole) have not been measured. It would be interesting to compare a repetitive putt design to these findings from a representative task design to assess if there are differences in gaze strategy on the target/hole as a function of task design.

In addition, we also found QE Dwell duration (QE Dwell in comparison to No QE Dwell) had no effect on impact spot consistency. This finding contradicts research which found QE Dwell is synonymous with maintaining a good stroke (Moore et al., 2012; Vickers 2007). We propose that in our current study, after striking the ball, participants did not keep their vision still and fixed on the spot where the ball was, prior to contact (in line with QE Dwell). Instead, post contact, participants engaged in a process of pursuit tracking (Spering & Montagnini, 2011). We suggest that participants tracked the ball after contact to gain feedback on speed of the green, green characteristics, roll of the green and topography of the green (Mackenzie & Sprigings, 2005) to inform future putts. More broadly, for future investigations, the QE Dwell and visual strategy findings suggest an Ecological Dynamics approach may provide a useful theoretical framework for understanding putting behaviour.

Use of a more ecologically valid task, compared to previous laboratory-based protocols can be considered a particular strength in this study. Performance in this representative task was closer to the putting success rates seen on Tour in comparison to performance data reported in laboratory studies using repetitive putts, where performance can reach up to 70%. In our study, the cohort of experts can be considered similar in putting ability, as performance (percentage success) on this representative task was not influenced by skill level (median split of average putts per round). However, when considering the location of errors associated with missed putts there was a difference based on skill level (median split of average putts per round) with lower skilled participants producing greater variability when the putt distance increased beyond 8ft. One implication of this finding is future studies may be better able to reveal differences in skill based performance if they require participants to employ a follow up putt (i.e., instructing the participant to continue to putt after the initial putt missed), at least when putting from distances greater than 8ft.

To better represent perceptual-cognitive demands of high-performance golf putting, this study was designed with the following features: variation of putt distance, variation of putt type, a representative putting surface (indoor putting facility with accurate stimp meter rating) and a task that enabled participants to complete their full putt routine. Enabling participants to complete their full routine may have contributed to the reduced QE duration found in our study. In the only other study allowing participants to use their full pre-shot routine, QE duration was in line with QE durations found in this study (van Lier et al., 2010). In contrast, when participants complete a repetitive putt design, typically they do not use their full pre-shot routine and reported QE durations are much higher (for example see Vine et al., 2011). In the present study our intention was to examine QE in a representative task design to allow a more accurate exploration of the impact of QE duration on performance.

We also conducted an analysis at the level of individual trials, to gain a greater understanding of the changes that occur from putt-to-putt, and help generate novel insights that can be disseminated into applied competitive golf. This analysis highlighted previously unreported variation in behaviour. Understanding variation is important when applying findings to elite golfers. Elite golfers are expected to compete on different courses around the world on a regular basis, so variation is inherent within the nature of their performance environment. Importantly, however, this variation makes it difficult to extricate golfer-specific changes from changes in the environment that cause golfers to adapt their routine (which leads to changes in performance). For future research it is recommended trials are analysed on an individual basis rather than using group averages, to understand how individuals vary over trials, and assess which factors contribute to reducing variation in performance.

Three main limitations of this study are identified for consideration. Firstly, the participants were not trained in a QE intervention, so did not consistently meet recommended QE duration. Further study is recommended whereby the participants are given a QE intervention, to explore what impact QE has on performance *in-situ*. Secondly, the study only had one session, so it is not clear if the variation in behaviour participants displayed is a true reflection of their behaviour. It is recommended that future research includes at least two sessions, to explore whether variation is consistent across sessions. Multiple testing sessions in the research environment would provide an ideal environment to explore and understand variation within highly skilled golfers and provide an environment to teach visual strategies and monitor behaviour and performance. This would enable researchers to develop a clearer understanding of which visual strategies (if any) are related to improvements in performance. Lastly, as we focused on early QE duration due to the emphasis on task difficulty (Walters-Symons et al., 2018), there has also been other literature that suggests that late QE duration is crucial for performance so further study is required capturing total QE duration (Vine et al., 2013).

3.5 Conclusion

Contrary to claims within the wider literature, in the present study we found a longer QE duration does not enhance performance in highly skilled golfers - when putting occurs within the context of a representative task. We suggest this finding is due to the nature of the task demands during a representative task design - just as in real competitions, our cohort of highly skilled golfers demonstrated inconsistencies within their routines, gaze behaviours, QE duration and performance, prior to putting. We believe these inconsistencies are caused by the golfers not having knowledge of the environment, due to changing environmental demands present in a representative design. In laboratory conditions, the environmental demands are stable, and golfers can quickly regulate their actions to the environment, effectively learning the putt. In contrast when using a representative task design in golf putting, a golfer is required to hit a new putt each time and as such there is greater need for the golfer to regulate their actions to the environment. By observing a highly skilled cohort of golfers using a representative task design (Brunswik, 1956) we were able to provide novel insights into the performance factors present in the applied domain, revealing that QE duration alone may not be able to predict performance. Further exploration is warranted to understand how QE duration links to performance, and if the findings from representative task designs differ from non-representative task designs using repetitive putts.

Chapter 4: Study 2a - Exploring the impact of a QE intervention on golf putting performance.

The current chapter details the rationale for, and results of, Study 2a. This study and the associated two studies (a mobile cognition study outlined in Study 2b: Chapter 5, and Chapter 6 a follow up study outlined in Study 2c), seek to explore the relationship between expertise and Quiet Eye (QE) status within the context of an indoor golf-putting environment. The series of studies have been designed to recreate QE interventions within current literature in an attempt to identify the mechanisms that underlie the QE phenomenon and to further develop the theoretical underpinnings of QE. The lack of theoretical knowledge underpinning QE is *"considered to be the greatest shortcoming of this research"* (Williams, 2016, p. 2).

The findings from Study 1 (Chapter 3: where QE duration was measured within a representative task design) generated questions regarding the view QE duration is key to successful putting. Subsequently, the findings from Study 1 provide little support for QE training, however, participants were not explicitly taught a QE intervention and early QE duration was captured so further research is needed in this area to explore whether these changes impact on the relationship between QE duration on performance. Wilson *et al.* (2016) have commented that performance advantage from QE intervention is one of the main findings from the body of evidence. Therefore, the aim of the present study is to assess whether a QE intervention can improve golf putting performance. Previous QE intervention studies have separated participants into either a control group or QE intervention training group (e.g., Vine et al., 2011), so currently a within participant QE intervention has not been reported in the literature. Accordingly, the present study has been designed to employ a within participant design to examine what impact a QE intervention has on performance.

4.1 Introduction

The QE intervention has been designed to increase a participant's Quiet Eye (QE) duration (as defined in Chapter 3), by asking participants to follow a set of instructions and highlighting differences between QE durations which are perceived to be more or less optimal (Williams, 2016). The use of QE interventions is motivated by research that suggests optimal QE duration is linked to superior performance (Vickers, 2016).

Consistent with this view, research has reported there is "*robust*" evidence (Wood et al., 2016, p. 1) to suggest a QE intervention does improve performance in both experts and novices in a range of sports and sporting tasks (including penalty kicks in soccer, basketball free throws, golf putting, and shooting) as well as in non-sporting environments (such as surgeons; see Vickers, 2016). Nonetheless, despite the obvious appeal of a technique which promises to deliver performance benefits, Williams (2016) warns caution should be applied before recommending the widespread use of QE interventions due to the lack of understanding on how QE interventions improve performance. To be clear, researchers have been unable to provide a theoretical explanation of why a longer QE duration is optimal and how this links to performance, particularly on an individual level (Gonzalez et al., 2017). Therefore, the present study was designed to recreate the QE intervention within golf putting, to provide greater understanding of the link between QE and performance.

To date, when QE intervention studies have been conducted in golf putting researchers have measured gaze behaviours on artificial surfaces, with repetitive straight putts from 3ft, 6ft and 10ft. QE interventions have typically been examined in laboratory settings, based on the assumption that findings will also apply to 'on course' performance. One attempt to examine the benefits of QE during real-world golfing was provided by Vine *et al*. (2011), in a study with highly skilled golfers that captured performance post QE intervention, over ten competitive rounds. In their study, a QE intervention was found to improve average putting performance (an average of 1.9 putts per round across ten competitive rounds) in comparison to a matched control group. In the QE intervention group, participants observed a video of their gaze behaviour and that of an expert golfer's gaze behaviour. Whilst watching the video, the researchers explicitly highlighted the characteristics of expert visual gaze. Participants within the QE intervention group were also given additional instructions to maintain a longer QE duration when putting. Participants in the control group only observed the video of their gaze behaviour, and that of an expert golfer's gaze, and were not given any instructions in relation to QE duration when putting. In contrast to the QE intervention group, the control group did not show any improvements in performance in the ten rounds after the intervention (Vine et al., 2011) and the authors concluded QE duration could account for 43% of the performance variance.

On first inspection the Vine *et al.* (2011) findings appear to be very compelling. It is important to note, however, that during the ten competitive rounds the authors did not carry out manipulation checks or measure QE duration. As a result, it is unclear whether the participants adopted the QE intervention during the competitive rounds. Furthermore, as there were no measures of QE duration taken in the competitive environment, the authors only reported the mean QE duration from their testing sessions in the laboratory. Furthermore, Vine *et al.* (2011), only reported mean QE duration between groups. Questions remain, therefore, about whether QE duration improves performance, at the level of the individual golfer, when putting is performed *in-situ* in the applied domain.

When examining QE duration and QE interventions outside the laboratory, the limited studies researching in this area have found individual differences in associated success, despite changes in gaze behaviours in line with the QE intervention instructions (*cf*. Mann et al., 2011; Panchuk, et al., 2014). These findings raise questions about the efficacy of QE in the applied domain and suggest the performance benefits of QE interventions may be dependent on the task and environment. In support of this view, findings from Study 1 (Chapter 3) in this thesis revealed there was a considerable level of variation within and between highly skilled golfers in their routines, gaze behaviours, QE duration and performance when using a representative task design. Moreover, optimal QE duration did not always lead to success and mean QE duration recorded were shorter than the recommended QE duration promoted in the QE intervention.

Furthermore, in Study 1 the putative benefits of QE duration for error recovery as outlined by Walter-Symonds *et al.* (2017), could not be found. That is, there was no difference in the success of a putt based on whether QE duration increased or decreased compared to in the previous putt. It must be noted, however, the golfers were not taught the QE intervention in Study 1 (as in Vine et al., 2011). It is important, therefore, to establish if highly skilled golfers who have learnt the QE intervention, as recommended within the literature comply with the QE assumptions. If this is the case, following QE training, it is expected that expert golfers will have a longer QE duration and earlier onset of QE, and a longer QE duration would be expected for hits rather than misses. Furthermore, if QE is effective, QE duration should be a reliable predictor of performance whenever a putt is associated with optimal QE – regardless of whether QE training has been administered.

Research has suggested one reason why QE duration may be effective for performance is when QE is incorporated into a golfer's pre-performance routine it improves attention in the seconds prior to initiating the motor action (Vine et al., 2011). A pre-performance routine can be defined as "*a sequence of task-relevant thoughts and actions which an athlete engages in systematically prior to his or her performance of a specific sports skill*" (Moran, 1996, p. 177). According to this view, QE duration provides the golfer with an external focus of attention (Wulf, 2007). An external focus has been found to be effective for performance, partly because it prevents participants from focusing on internal or external distractions (Singer, 2002).

In principle incorporating QE durations into existing pre-performance sounds very appealing from an applied perspective. In practice, however, evidence from research exploring the benefits of teaching golfers pre-performance routines prior to putting has revealed golfers have strong individual preferences about what behaviour and psychological skills they adopt and as a result golfers do not always adhere to interventions (Cohn et al., 1990; Cotterill et al., 2010; Thomas & Fogarty 1997). Individual differences and the golfer's current appraisal of the situation had a marked impact on both performance and a golfer's ability to consistently adopt new pre-performance routines (Cohn et al., 1990; Cotterill et al., 2010; Thomas & Fogarty 1997). Additionally, when researching the impact of an intervention on teaching a pre-performance routine in golf, not every session benefited every golfer and the reasons behind this are unclear (Cohn et al., 1990; Thomas & Fogarty 1997). These findings are also consistent with other research suggesting experts do vary in their ability to adopt a pre-performance routine with differences recorded in temporal components and exact behaviours completed (Cotterill et al., 2010; Cotterill, 2011).

Currently research into golfers learning the QE intervention has shown a good learning effect and retention of the QE intervention instructions on a repeated basis, for example, in Vine and Wilson (2010) study participants showed stable QE durations in the 2-day-delayed and the 5- day-delayed retention tests. However, in Klostermann and Hossner (2018) study, where nineteen undergraduate participants were trained in a QE intervention to use during a throwing performance task, participants showed longer QE durations in the post-test in comparison to the pre-test, however, in the retention test there was no increase in QE durations from pre-testing. Therefore, taken together with the previous research on pre-performance routines in golf putting, this study aims to examine whether participants consistently adopt the QE intervention instructions i.e., demonstrate behaviourally stable QE (Williams et al., 2002).

Rationale

Given the concerns outlined above it is important to explore whether a) the QE training intervention leads to a performance enhancement for all participants; b) whether all participants are able to learn and consistently adopt the pre-performance routine taught as part of the QE intervention. Furthermore, based on our findings in Chapter 3, with elite golfers we do have reservations around why a) one would want to train QE given the previously presented findings, and b) why an increase in QE would be expected to improve putting given the findings previously reported, particularly in light of the lack of theoretical grounded for why a longer QE duration is optimal for performance. These questions are important from a theoretical perspective, to aid basic understanding of QE. More importantly, perhaps, the answers to these questions are essential from an applied perspective, allowing decisions about the appropriate use of QE interventions to be evidence based. Therefore, the aim of this current study is to conduct a within participant design study, whereby a participant completes a series of putts in a control condition to act as a comparison, then on the same day completes/receives a QE training intervention, and is then asked to complete another series of putts adopting the QE intervention instructions (identical to the control condition, i.e., from the same putt positions and on the surface but in a different putt order). The participant's gaze behaviour and performance will be measured in the putts following the QE intervention, to provide an opportunity to measure gaze and performance on a trial by trial basis and for manipulation checks to be carried out.

The current study therefore addresses three specific hypotheses. i) QE training will lead to an increase in QE duration, ii) increases in QE duration will lead to an increase in putting success rates, and iii) optimal QE durations will be associated with the highest level of performance (% putts holed and smallest error dispersion) and iv) expert performers will have a longer QE duration, with an earlier onset in comparison to less expert performers. We acknowledge that our findings from Chapter 3 do not support these hypotheses but these hypotheses are set based on the fact the participants did not receive a QE intervention in Study 1, and based on the balance towards the evidence in the literature supporting QE intervention improving performance (Lebeau et al., 2016).

4.2 Methodology

4.2.1 Research Design/Methodology

A repeated measures experimental design was used with all participants experiencing putting under both control conditions and following QE training, referred to as QE putts.

4.2.2 Participants

Twenty eight participants took part in the study (20 males and 8 females). All golfers were right handed and right eye dominant, with normal or corrected to normal vision. Mean age was 24.2 (± 6.4) years. Average handicap was +1.7 (± 6.4). Mean golf eperience was 12.8 (± 5.69) years, with an average weekly practice of 15.5 (± 11.5) hours, an average putts per round of 31.3 (± 2.84), and average greens in regulation of 56.2% (± 10.1). Average putts holed from 6ft straight during baseline testing was 85% (± 21.1).

4.2.3 Procedure

Ethical approval was granted by the University of Stirling Psychology Ethics Committee. All procedures were in accordance with the Declaration of Helsinki ethical principles for collecting research with human participants. The lead researcher contacted the National Governing Body, and the University of Stirling Performance Director for golf and local golf clubs, for permission to speak to players matching the eligibility criteria, to determine interest in participating in the study. The lead researcher then met interested players to explain the study requirements and related information. Following this meeting, players were asked to confirm their involvement in the study by returning a signed copy of the informed consent sheet and demographic information to the lead researcher. Players were made aware that: participation was not a requirement; it was voluntary without obligation; and it had no influence on training and selection. There was no coercion to participate from coaches or the lead researcher.

Participants attended testing sessions individually and an ASL mobile eye tracker was fitted to the participant by the lead researcher (consistent with Study 1, see Chapter 3). This approach was also consistent with previous research carried out on visual gaze in putting (Vine & Wilson, 2010; Wilson & Pearcy, 2009; Wilson et al., 2009). Participants used their own putter (fitted by a golf professional prior to the study to ensure consistency for all participants) and Srixon AD333 Tour golf balls were provided consistent with Study 1. Participants were given an opportunity to ask any further questions prior to commencing the experiment. Participants were asked not to discuss the experiment outside of the study session.

The ASL mobile eye tracker was calibrated using five markers positioned near the golfers' feet when standing in putting posture and addressing a golf ball (consistent with Study 1). Participants completed a standardised warm up (12 practice putts; 6 straight and 6 sloped putts with different putt locations and into a different hole in comparison to the representative task) on the indoor artificial surface (with a stimp meter rating of 10.2). Following the warm-up, participants completed a putting task of 70 8ft straight putts (pre-intervention- control condition), taken from 5 different putt positions. The participants then completed the brief QE intervention (outlined in Chapter 2) before completing another 70 putts (post-intervention: QE putts) from 8ft straight. The order putts were taken in was unique for each golfer, generated using a nested design whereby the putt position was randomised across participants, with the constraint that they putted twice from each location in each block of ten putts. The post intervention putts (QE putts) were taken from the same position as the control putts but in a different order (Figure 12). Before every trial the lead researcher placed the ball on the identified position (the marker could only be revealed if shinning the UV light on the green). Participants were given forty seconds to complete each putt; they were asked to carry out their normal putting routines and to take a break after every ten putts. On average participants took 1 hour to complete the 70 putts. After all putting was completed, participants were given a chance to ask any questions and reminded about their ability to withdraw. Participants were also given the researcher's contact details to give the participant a chance to ask any questions in the future.

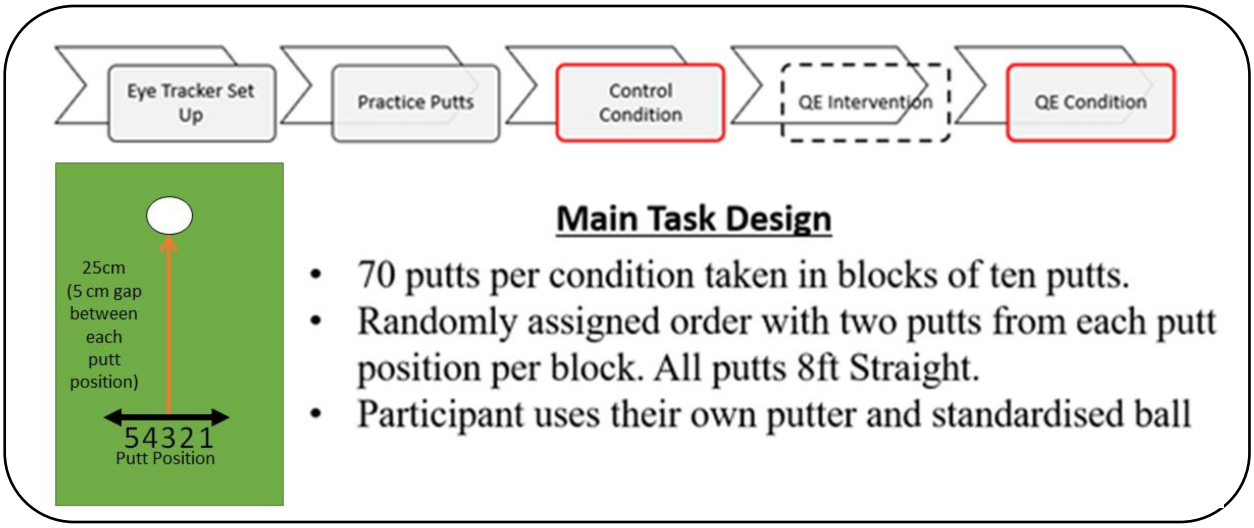


Figure 12. Schematic illustrating the main features of the methodology employed in Study 2a.

4.3.2.1 QE intervention

The QE intervention was adapted from Vickers (2007), consistent with previous QE training research (e.g., Harle & Vickers, 2001; Vine & Wilson, 2010). Participants were asked to:

- Assume your stance and align the club so the gaze is on the back of the ball.
- After setting up over the ball, fix your gaze on the hole. Fixations toward the hole should be made no more than 3 times.
- The final fixation should be a QE on the back of the ball. The onset of the QE should occur before the stroke begins and last for 2 to 3 seconds.
- No gaze should be directed to the clubhead during the backswing or foreswing.
- The QE should remain on the green for 200 to 300 ms after the club contacts the ball.

The intervention was taught following the control putts (on the same day) because pilot testing revealed participants struggled to stop performing the QE routine once they had learnt it within the same session. Critically, the presence of clear carry-over effects once the QE routine had been learned meant it was not possible to counterbalance the order of QE and control putts. To be clear, the change to delivering the QE intervention within participants highlighted the potency of QE training - a previously unreported learning effect which imposed a significant constraint on the design of the intervention.

4.2.4 Measures

4.2.4.1 Visual Search Behaviours

Visual search behaviours were captured using ASL XG Mobile Eye Tracker, consisting of mobile eye tracker lenses and EyeVision software (ASL Results Pro Analysis, Argus formally, ASL) installed on a laptop (Dell Inspiron6400). Consistent with previous research (Vine et al., 2011) gaze location is depicted by a crosshair (+) cursor (representing 1° of visual angle) in a video image of the scene (spatial accuracy of ± 0.5° visual angle; 0.1° precision, 30 Hz frame rate). The lead researcher checked the accuracy of the calibration throughout the testing session, re-calibrating whenever necessary (e.g., after a pupil recognition loss >100ms or if the calibration had been lost). The eye tracker was also calibrated at the start of each putt block. All analysis was completed post testing, using event by event analysis specific to the area of interest (i.e., the ball). Blink frequency and blink duration (ms) were also monitored via the use of a blink detection algorithm. If pupil recognition was lost during a recognised fixation (for example, due to a blink) for less than the time specified as “Maximum Pupil Loss” (100ms), then the fixation does not end, and fixation duration continues. If pupil recognition is lost for a longer period (>100ms), the fixation is considered to have ended at the beginning of the recognition loss period. Additional measures of ‘total viewing time of the ball’ (3◦ visual angle throughout the putt routine prior up until viewing time on the ball prior to QE as a continuous measure); ‘viewing time on the ball prior to QE’ (3◦ visual angle on the ball prior to the onset of QE) and average fixation duration were captured.

4.2.4.2 Quiet Eye (QE) Durations

QE durations were calculated using Quiet Eye Solutions Visual-in-Action software (Version 1, QE solutions Inc.) and ASL Results Pro (ASL Results Pro Analysis, Argus formally, ASL). QE durations (consistent with total QE); the QE onset had to begin before movement initiation of the backswing but could continue through the putting movement (e.g., as in Causer et al., 2017). QE offset occurred when gaze deviated from the target (ball or fixation marker) by more than 3° of visual angle, for longer than 100 ms (Moore et al., 2012; Vickers, 2007). The absence of a QE fixation was scored as a zero. (>100ms focused on the ball, with less than 1 degree of visual angle (Vine et al., 2015). The early phase of the QE (QE-early) started at QE onset and ended with the initiation of the backswing). QE Dwell – a minimum of 200ms with the eyes focused on the green after hitting the ball (Vine et al., 2015).

4.4.2.3 Performance

Performance was assessed by the number of successful putts. Putting error was measured by calculating absolute distance from the hole (cm) and angle from the hole (degrees). These values were calculated manually using Kinovea (Version 0.8.12, https://www.kinovea.org/) from photographs of each trial, off-line, after testing was completed. Photographs were taken by a camera on a fixed stand which allowed the picture to be taken from directly above the hole. The stand was placed in the same position at each hole for consistency.

4.2.5 Statistical Analysis

In all analyses significance was accepted at $p < 0.05$. To establish whether the QE intervention was effective, the initial analysis explored whether QE duration changed pre- and post-intervention using repeated measures ANOVA with factors Condition (2: Control, QE Intervention) *Time (7: 500-1000ms, 1000-1500, 1500-2000, 2000-2500, 2500-3000, 3000-3500, >3500ms). Paired *t*-tests were also conducted to explore differences in other visual measures, such as total viewing time on the ball, viewing time on the ball prior to QE and average fixation between the control and QE intervention conditions. A regression was completed to assess whether QE duration was stable and consistent across the seventy trials in both the control and QE conditions and whether there was a difference in slopes between the two conditions.

To explore what impact the QE intervention had on mean performance (% putts holed) a paired *t*-test was completed to assess differences between the control and QE intervention. Two additional analyses were performed to assess the effects of putt position and put block. To assess if there was a difference in performance based on putt position a repeated measures ANOVA examined success rates with factors of Condition (2) and Putt Position (5). Similarly, a repeated measures ANOVA was employed to see if there were any differences in performance in each block (ten putts) to assess for practice effects, with factors of Condition (2) and Putt Block (7). Putt block is defined by the intervals, such that each block consists of 10 putts, resulting in a total of 7 blocks for each condition, with Block 1 representing the first ten putts in the condition and Block 7 representing the last ten putts in that condition.

To further explore whether learning the QE procedure enhances performance the relationship between putting success and block was examined for both control and intervention conditions using multivariate linear regression. The use of regression analyses rather than traditional differences testing has been advocated by Williams (2016) on the basis that regression offers greater sensitivity.

In addition, to explore whether performance varied as a function, QE duration putting success rates were also examined as a function of QE duration, using repeated measures ANOVA with factors of Condition (2) and Time bin (7). The -time bins were 500-1000, 1000-1500, 1500-2000, 2000-2500, 2500-3000, 3000-3500, >3500ms.

As in Study 1, analyses were also carried out to explore the pattern of errors made when putts were missed. These analyses examined whether there were any differences in mean error based on QE duration. The circular statistics toolbox in MATLAB (Berens, 2009) was used to explore if there were any differences in error angle based on the control putts in comparison to the putts taken after the QE intervention. SPSS was used to assess whether there was any difference in error length (cm) pre and post the intervention. Also, an additional experimental analysis (Appendix 1) using the circular statistics toolbox was used which transforms cartesian coordinates (reflecting the position of the ball relative to the hole) into two dimensional vectors (coding distance and direction) was used, allowing the mean distance and direction to be calculated to compare the two groups (lesser and higher than average QE duration). To explore between groups, Watson-Williams tests were conducted to assess whether the mean directions were statistically different.

4.3 Results

4.3.1 Visual strategies Pre and Post Intervention

To explore if the QE intervention was successfully implemented, analysis on trial by trial basis using a repeated measures ANOVA, Condition (2: Control, QE Intervention) *Time (7) was conducted. As shown in Figure 13, findings highlight there was an increase in QE duration after the intervention, with a significant interaction [$F_{(2.238,\ 46.989)} = 8.760$, $p < 0.01$, $n^2 = 0.05$] and main effects found for condition [$F_{(1,21)} = 31.166$, $p < 0.01$, $n^2 = 0.003$] and time [$F_{(1.595,\ 33.504)} = 27.800$, $p < 0.01$, $n^2 = 0.470$]. Post hoc paired t-test revealed significant differences in trials in the bin 2000 to 2500ms [$t_{(42)} = 7.724$, $p < 0.001$].

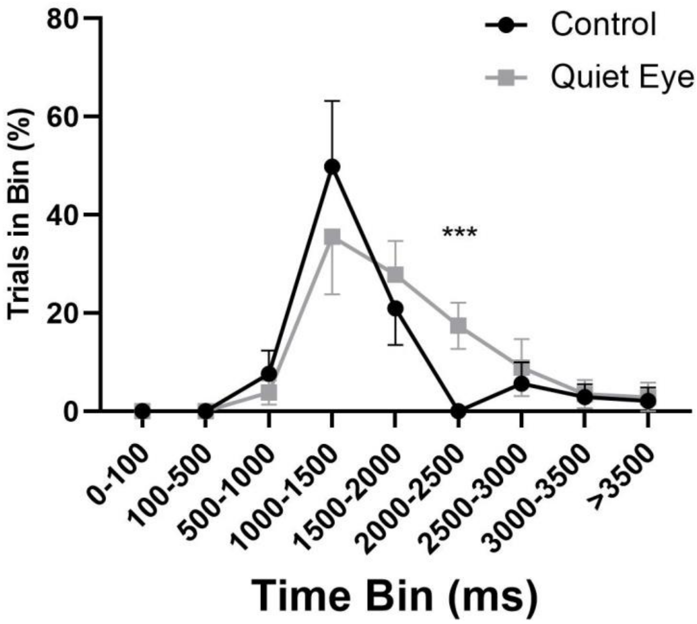


Figure 13. QE duration following the QE intervention in comparison to the control condition (change in % trials in each time bin).

To explore the impact of the QE intervention, paired *t*-tests were conducted for a range of visual gaze variables (see Table 8). The significant increase in viewing time on the ball pre QE and average fixation, suggest the QE intervention changes more than just QE duration alone and these gaze measures warrant further investigation. It was also of note relative to the function of QE duration, that early QE duration significantly increased post intervention, however QE Dwell did not.

Table 8. Change in Gaze Variables following the QE intervention.

	Control Mean	***QE Mean***	***Difference***	***SE of difference***	***t ratio***	***Df***	***Adjusted P value***
Total Time Viewing Ball	2.376	3.302	-0.926	0.476	1.946	44	0.06
Viewing time on Ball Pre QE	1.362	2.004	-0.642	0.264	2.427	44	0.02
Avg. Fix. Duration	0.356	0.477	-0.122	0.068	1.788	44	0.08
Early QE	0.552	0.828	-0.276	0.136	2.03	44	0.05
QE Dwell	0.234	0.223	0.011	0.047	0.233	44	0.817

4.3.2 QE duration over the course of the condition

To check if QE duration was being applied consistently throughout the trials in both conditions (control and QE) a regression was conducted. As seen in Figure 14, the linear regression revealed there was no difference in the slope [$F(1,3076) = 1.484$, $p = 0.223$], i.e., QE duration was consistently adopted throughout each condition and there was no variance across trials in the 70 putts. However, there was a significant difference in elevations between the two conditions, [$F(1,3077) = 105.5$, $p < 0.0001$], highlighting QE duration was different meaning that QE duration changed between the control and QE condition.

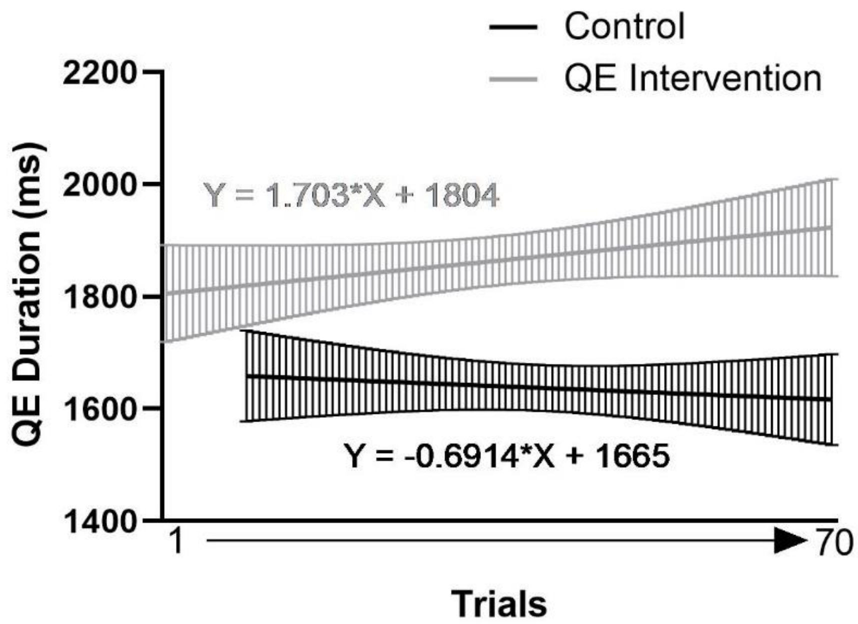


Figure 14. The relationship between trial number and QE duration across for the control condition (black line and 95% CI represented by black lines) and QE condition (grey line and 95% CI represented by grey lines). There is no difference in slope between the two conditions.

4.3.2: Performance

Having established that the QE intervention produced the desired change in gaze behaviour the key question is how putting performance is affected. As shown in Figure 15 (Panel A) there was an overall improvement in performance (mean putts holed) in the QE condition (post-intervention: 72% ± 2) in comparison to the control condition (pre-intervention: 68 % ± 2). Analysis confirmed this difference in performance between the two conditions was statistically reliable ($t_{(44)} = 2.326$, $p = 0.02$). Figure 15 (Panel B) also illustrates the size of the QE effect in each participant, illustrating that performance increases were seen in 15/28 participants, ranging from an improvement of 1% to 26%, revealing considerable individual differences in the effect of the QE intervention on performance.

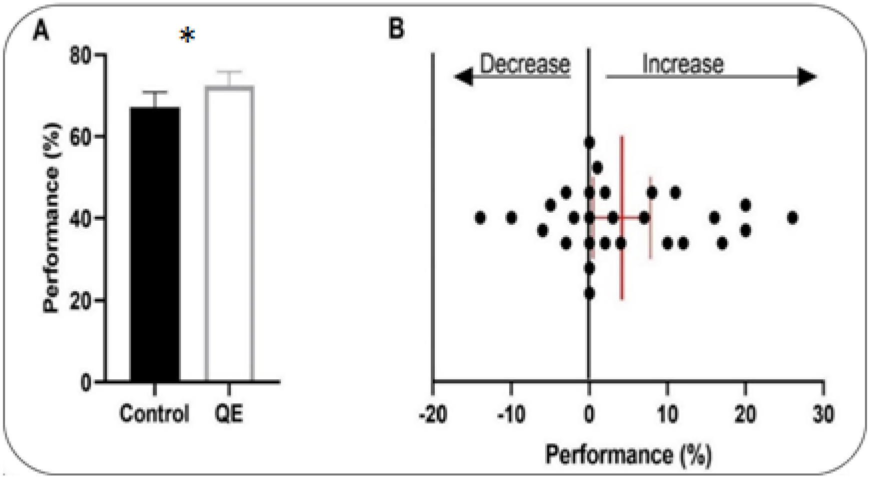


*Figure 15. The impact of a QE intervention on performance Panel A represents mean % putts holed (and 95% CI) for the control condition and QE intervention. The QE intervention was associated with higher mean performance. * = p < 0.02. Panel B reflects performance change on an individual level highlighting not every participant improved their performance (Mean and 95% CI indicated by red lines).*

Given the variability between participants noted above the data were also examined as a function of putt position, to examine whether the performance improvement was present at all putt positions. Follow up analysis examined putting success independently at each position, revealing there was a significant improvement in performance at Position 1 [$t_{(24)} = -2.431$, $p = 0.023$], but no reliable difference in performance between the control and QE conditions at the other putt positions ($p >$ 0.05). Figure 16 illustrates the change in performance at Position 1 for each golfer, once again revealing considerable individual differences in the effect of the QE intervention.

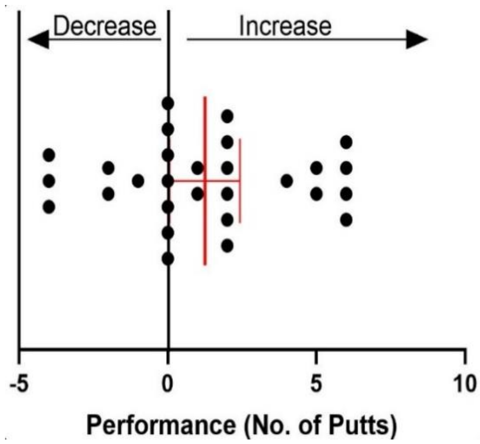


Figure 16. Difference in the number of successful putts at Position 1 following the QE intervention (Mean and 95% CI indicated by red lines). Each line represents a single participant; 15 participants exhibited an improvement, 6 showed a decline in performance, a decline in performance, and 7 participants exhibited no change.

Putting was performed across a series of blocks of trials, consequently it was of interest to explore if there was a significant difference in performance as a function of block (10 putts formed a block, with 7 blocks in total for each condition). These data, shown in Figure 17, were subjected to ANOVA, which revealed a significant main effect of Condition ($F_{(1, 378)} = 15.97$, $p < 0.0001$) consistent with more putts being successfully holed in the QE condition. The analysis also revealed a main effect of Block ($F_{(6, 378)} = 7.284$, $p < 0.0001$), highlighting there was an overall increase in performance across Blocks (Figure 17). In addition, there was a significant interaction between Condition and Block ($F_{(6, 378)} = 2.577$, $p = 0.0185$), reflecting the difference between Control and QE conditions varied as a function of Block. Importantly, post hoc testing revealed there was only a reliable significant difference in performance between control and QE condition for Block 1.

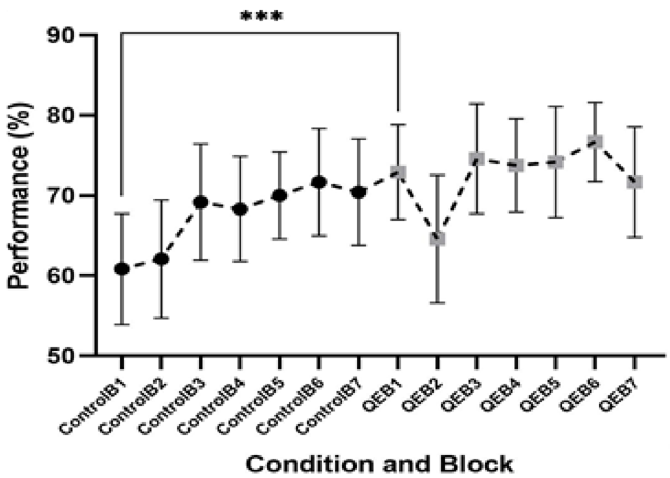


*Figure 17. Difference in performance (% putts holed and 95% CI) per block (10 putts per block) across the control and QE intervention putts. There was an improvement in performance for QE Block 1 in comparison to Control Block 1 (*** = p<0.001).*

4.3.3 Closer inspection of the performance data

Finding that performance benefits associated with QE training appeared to vary (by putt position, putt block and across participants) raises questions regarding the consistency of the effect. Moreover, by design the QE intervention always came after the control intervention (meaning the participants had already completed 70 putts in the control condition on the same putting surface prior to completing the QE intervention) raising the additional possibility that practice effects may be present. Thus, to investigate the pattern of performance in more detail (going beyond traditional testing of the overall average change in performance) a multivariate linear regression was conducted. These data presented in Figure 18, which reveals a clear change in performance across blocks for the control condition, but no obvious change across QE blocks. Analysis confirmed that in the control condition there was a strong significant positive relationship between performance and block, with the highest performance occurring during later blocks ($p <$ 0.001; Pearson co-efficient $r = 0.94$; $CI = 0.64$ to 0.99). In contrast, for the QE intervention, there was a non-significant relationship, meaning that performance did not improve across blocks ($p > 0.05$; Pearson co-efficient $r = 0.35$; $CI = -0.54$ to 0.87).

As Figure 18 shows, the data clearly suggests performance improved over the control blocks, reflecting a practice effect, but then plateaued, showing no further change during the QE blocks. This finding is consistent with the earlier analysis, where a significant difference was only found in Block 1, when performance was at its lowest in the control condition. Finally, additional analysis was carried out to compare the slopes in each condition. This analysis confirmed there was a significant difference in the elevation and intercepts between conditions [$F_{(1,11)} = 8.815$, $p = 0.01$], confirming there was a different effect of block in the two conditions, with practice only improving performance during the initial control blocks.

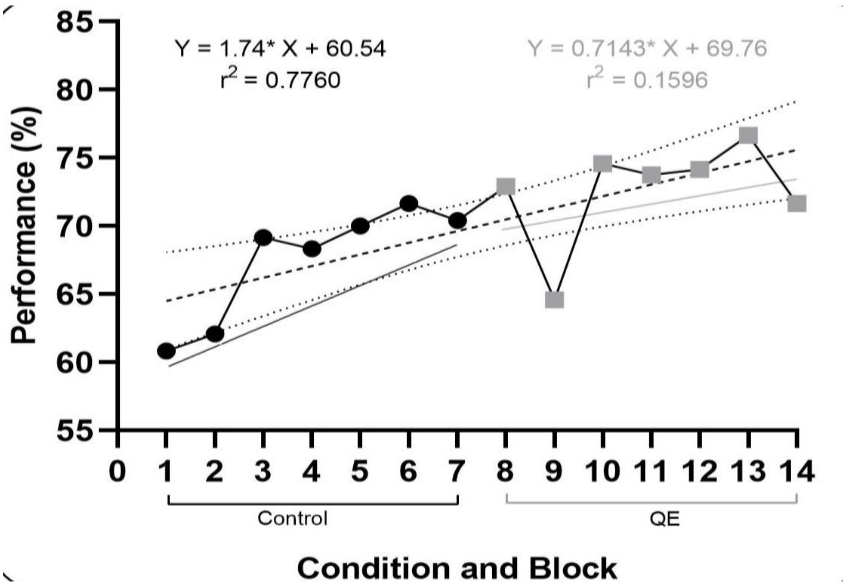


Figure 18. Performance (% putts holed and 95% CI) for QE and control conditions as a function of block Block 1 represents putts 0-10, block 7 represents putts 60-70 for the control condition, block 8 represents putts 0-10 and block 14 represents putts 60-70 for the QE condition. For the whole testing session (black dashed line) the best fit linear regression line is illustrated (along 95% CI, black line mini dashes),and each condition the best fit linear regression line is also illustrated (black line control and grey line QE) revealing a significant increase in performance during the control condition, but no change during QE.

4.3.4 QE duration and performance on a trial by trial basis

Having examined performance as function of the QE intervention, the next set of analysis examined the relationship between QE duration and performance, as illustrated in Figure 19. As shown in Figure 19, the greatest success was associated with 1000-1500ms, a QE duration shorter than the recommended QE duration (2-3 seconds). These data were analysed using ANOVA, revealing a significant interaction [$F_{(2.402, 50.433)}$ = 3.205, p = 0.006, n^2 = 0.260] and significant main effects for condition [$F_{(1,21)}$ = 6.632, p = 0.018, n^2 < 0.001] and time [$F_{(1.642,34.490)}$ = 24.744, p < 0.01, n^2 = 0.456]. As can be seen in Figure 19, and consistent with the gaze behaviour reported above, the QE intervention altered the profile of successful putts, with more successful puts at longer QE durations than in the control condition. Nonetheless, the assumption that longer QE durations should be associated with better performance is clearly not supported by the data – success was highest for the shortest QE durations in both control and QE conditions, however statistically post hoc testing of performance in each time bin found no differences between conditions after Bonferroni corrections (1000-1500ms: *Pbonf* = 0.225, 1500-2000ms: *Pbonf* = 1, 2000-2500ms *Pbonf* = 0.672, 2500-3000ms*: Pbonf* = 1).

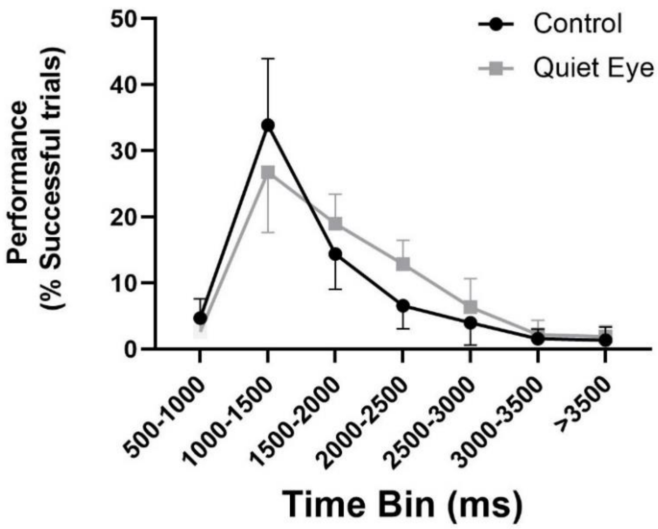


Figure 19. Difference in performance between the QE intervention and control condition, based on QE duration time bins Greater performance was recorded at shorter QE durations (< 2000ms).

4.3.5 QE duration and error location

The final set of analysis examined the error data (missed putts). The final position of each missed putt was recorded, and the location data (angle and distance) were examined as a function of QE intervention comparing the error in the control putts to the error in QE putts taken after the intervention. Figure 20 and Table 9, present data, representing the distribution of angle error around the hole.

Table 9. Properties of angular data for missed putts, representing central tendency and spread for both the control and QE putts.

	Mean Resultant Vector (°)	*R Length (0,1)*	*Variance (0,1)*	*SD*	*Raleigh Test of Uniformity (p = < 0.05)*
Control	170.15	0.76	0.24	0.70	<0.001
QE	173.53	0.78	0.22	0.66	< 0.001

The error locations in both conditions were long and mainly towards the right of centre. To assess if there were any differences in angle location a Watson-Williams test was used to compare the distribution of errors around the hole between the two groups. Critically there was no difference between the two groups [$F_{(1,880)} = 1.45$, $p = 0.228$].

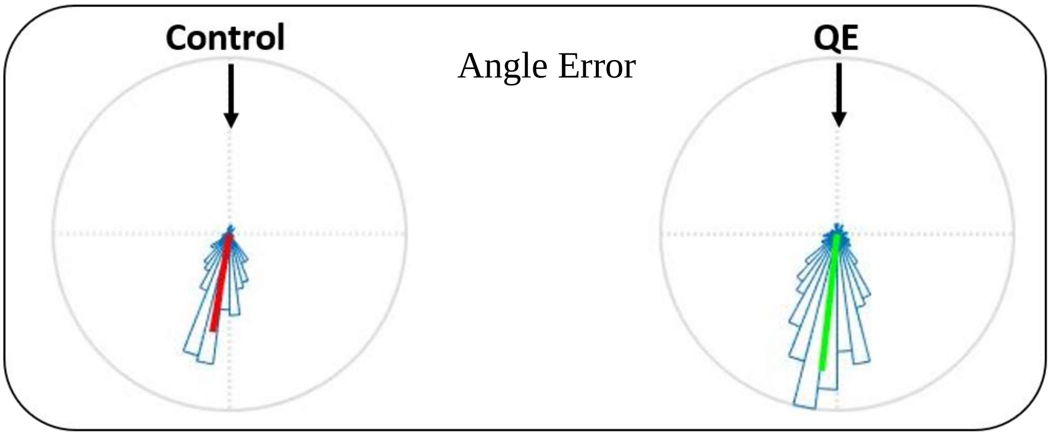


Figure 20. Angle histograms to represent the distribution of angle location in the missed putts (with the centre of the graph representing the hole, the two grey dotted lines separating a short/long miss and miss left/right of centre, the outer ring represents the largest mean angle error for that data set). The arrow indicates the direction of the ball from the putter. Each plot represents the distribution of missed putts around the hole, shown separately based on control and QE intervention putts. The blue lines represent the frequency of errors around the hole. The red lines indicate the direction and magnitude of the mean resultant vector for control and the green lines indicate the direction and magnitude of the mean resultant vector for QE putts.

In terms of the distance from the hole i.e., how far the ball landed away from the hole, mean scores indicate that error in distance between the control distance error (16.07cm ± 9.42) and the QE distance error (17.87cm ± 9.35) was similar. Paired *t*-test confirmed there was no difference in distance length $t_{(404)} = .453$, $p = .651$.

4.4 Discussion

The current study was designed to examine the impact of a QE intervention on golf putting performance. More specifically, the study was interested in exploring whether all participants are able to learn and consistently adopt the pre-performance routine taught as part of the QE intervention and if the QE training intervention led to a performance enhancement for all participants. Consequently, 28 highly skilled golfers took part in a within participant design study to examine what impact a QE intervention had on performance. Results revealed that consistent with the predicted hypothesis, QE training did increase QE duration as analysis of the gaze behaviour demonstrates the brief QE intervention was successful in creating a change in visual strategy in accordance to the QE intervention instructions (Vickers, 2007) i.e., participants increased their mean QE duration following QE intervention in comparison to the control condition (Vine et al., 2011).

After the intervention, highly skilled golfers demonstrated an earlier onset of QE in comparison to pre intervention. The ability to change behaviour so quickly from their 'norm' highlights the trainable nature of QE duration and the ability of participants to learn a QE intervention, despite the QE intervention requiring a change from their typical gaze behaviour. When considering whether participants could consistently follow and adopt the QE intervention instructions as part of their pre-performance routine, regression analysis indicated QE durations were stable across the testing in each condition, therefore, it could be concluded, consistently applied. However, analysis of visual gaze strategies on a trial by trial basis provided evidence to suggest participants did not always adopt the QE instructions, highlighting that even highly skilled golfers do not consistently complete the same behaviours every time in their pre-shot routine. Furthermore, following the QE intervention participants also spent a greater time looking at the ball prior to the QE duration, highlighting that QE training may change additional gaze behaviour to that of QE (Wilson et al., 2016). Interestingly related to the function of QE duration, early QE duration did also significantly increase post the intervention, however, QE Dwell did not. Further study is warranted to explore the influence of the QE intervention on wider gaze strategies related to performance.

To help gain further understanding on why these specific changes in gaze behaviour are happening, an Ecological Dynamics approach may help to shed further light on how visual strategies improve performance (Davids & Araújo, 2016) as it can offer a framework that explores gaze behaviour and performance through studying the interaction between the athlete, task and environment (Dicks et al., 2009). In support of this researchers who explored factors beyond QE have found during the basketball pre-shot routine, prior to taking a free-throw picking up environmental information crucial for successful performance, (de Oliveira et al., 2006; Oudejans et al., 2005).

Having established that the QE intervention was successful in changing gaze behaviour, the primary aim of the study was to assess whether this would lead to changes in putting success. Assessment of putting success rates revealed after the QE intervention performance did significantly increase (in comparison to the control condition), indicating a longer QE duration does lead to improved putting performance in highly skilled golfers. However, caution must be applied when interpreting these findings. Firstly, when considering the findings on an individual level not all participants improved their performance after the QE intervention. Secondly, when the QE data was analysed on a trial by trial basis the greatest level of success was in the control condition with a QE duration 1000-1500ms. Thirdly, when the data was examined for each putt position the benefit of QE training was only evident at 1 of the 5 positions. Furthermore analysis of the data across the testing sessions revealed QE effect was restricted to the first block of trials. Lastly, and most importantly, regression analysis revealed the overall benefit of QE most likely reflects a practice effect. That is, performance improved with practice as participants completed the control condition, but no further improvement was present following the QE intervention. The effects of practice were systematically linked to the QE condition because the experimental paradigm design employed a fix task order, with QE always following control putting. Taken together, the increase in performance produced by the QE intervention putts in comparison to the control putts may reflect little more than a practice effect.

As noted above, the greatest difference in performance between the control condition and intervention condition was in the first block – when performance in the control condition was at its lowest (before practice had accrued). The fact repeated practice of the same putts is sufficient to produce performance benefits has important implications when disseminating findings to athletes and coaches, because repetitive putting is not a feature of real world competitive golf (van Lier et al., 2011). The present results suggest experimental manipulations which include repetitive putting may provide evidence of improvements in performance (due to practice), but the putative benefits may not transfer effectively to real world applied conditions where each putt is unique and only taken once.

The current study also examined individual variability in performance. A focus on intra-individual variability when exploring QE duration in athletes is currently missing, as the current analyses in literature are dominated by average measures across participants (Davids & Araújo, 2016). Consistent with Study 1, the present data showed considerable variation both within and between participants – in terms of both QE duration and performance. More importantly, perhaps, the analysis presented in the current study revealed the findings reported in QE studies may depend on the nature of the analysis carried out. In the present case an initial global assessment (based on group average data) suggested QE training was effective. In contrast, when performance was examined as a function of QE duration, it was clear the optimal QE duration did not lead to enhanced performance in comparison to shorter QE duration. Similarly, analysis of the data over trials (using regression) presented a quite different picture – strongly pointing towards practice effects rather than QE benefits per se. To be clear, analysing the impact of QE duration on performance on a trial by trial basis (matching how performance is assessed in competitive environments) highlighted that recommended QE duration did not always lead to the optimal performance – contrary to predictions within the wider literature. The present findings highlight analysing mean QE durations and then interpreting these findings in the context of the competitive golf environment can be misleading. Therefore, further investigation into the effects of QE on performance is warranted.

By extension, the present findings raise serious questions about the efficacy of QE interventions, and whether increases in QE duration always lead to enhanced performance. Despite exhibiting recommended gaze behaviours in line with the QE instruction, the QE duration times in our study were lower than those reported in literature (e.g., Vine et al., 2011) and not all participants exhibited an overall increase in performance following the QE intervention. There was also a large degree of individual differences present within the QE data. Taken together, these findings would highlight the need for QE research to shift towards understanding critical threshold bandwidths which could be distinguished according to task constraints and individuals (Davids & Araújo, 2016; Harris et al., 2020).

In this present study the hypothesis was based on QE theory and research (Moore et al., 2012; Vickers, 2007; Vine et al., 2011), that increases in QE duration will lead to an increase in putting success rates, and optimal QE durations will be associated with the highest level of performance. However, we could not provide support for either of these hypotheses within our findings, as a number of findings oppose these hypotheses. For example, we found that shorter QE durations (<2000ms) led to participants being able to successfully hole the ball and led to more success than longer QE duration (>2000ms). One reason for this success despite the shorter QE times, could be explained through Klostermann *et al.* (2014) findings which suggest when the target becomes predicable, consistent with repetitive task design long QE durations are not required as less information needs to be processed over the QE period. However, there was no decline in QE duration in relation to practice in this study and this explanation cannot account for why QE duration of less than <2000ms were associated with successful performance in Study 1, which adopted a representative task design utilising more unpredictable targets. Therefore, questions remain about the function of QE duration and the underlying mechanisms behind how QE duration improves performance.

In this present study and consistent with Study 1, putts associated longer QE durations did not lead to success. However, in support of our findings other studies have reported successful performances with QE duration of less than <1500ms in golf putting (Campbell et al., 2019; van Lier et al., 2010) and QE intervention throwing task QE duration <1000ms (Klostermann & Hossner, 2018). Furthermore, in our study findings revealed the same QE duration could lead to both successful and unsuccessful putts. These findings are not in line with the QE theory and associated assumptions (Vickers, 2007), however, are consistent with some of the problems reporting in literature when practitioners have tried to implement optimal QE recommendations (Farrow & Panchuk, 2016). Lastly, we found there was no difference in error location (distance or angle) between the control putts or QE putts. Our findings are in contrast to QE findings which have found successful is associated with longer QE durations in comparison to unsuccessful shots (Vine & Wilson, 2010; Vine et al., 2011).

Overall our findings indicate a number of unanswered questions remain about the relationship between QE duration and performance. The ambiguity in findings reflect the wider issue that further work on understanding why a longer QE duration is beneficial for performance is required. Without this further understanding it does not seem prudent to recommend QE intervention training as a performance enhancing strategy, particularly considering our findings here and from Study 1 whereby golfers are still able to putt successful without having a longer QE duration. Crucially it is still not clear what a QE intervention is specifically training and how that leads to a performance improvement. The findings at an individual level and at a trial-by-trial basis are concerning from an applied perspective. These findings also highlight the potential pitfalls of using repetitive putts and mean averages to inform recommendations for applied practice which is characterized by unique putts. Future study is therefore essential to address the efficacy of QE intervention for highly skilled golfers. Study 2b (Chapter 5) will explore neural activity and it is hoped this will enable us to "*explore more precisely the cognitive processes and theoretical mechanisms that underlie the quiet eye effect in target sports*" (Campbell & Moran, 2014, p. 371). We will also conduct a follow up study in Study 2c (Chapter 6) to explore the QE intervention over multiple sessions to explore if longer QE duration is more effective for performance when accounting for practice. Taken together as a collective of studies will help to confer the efficacy of a QE intervention for highly skilled golfers.

4.5 Conclusion

The current study suggests the design of the testing session has a significant impact when comparing pre- and post-training performance within individuals. The study was designed using a fixed task order due to the fact pilot testing revealed participants were unable to 'unlearn' the QE intervention within the same testing session. As a result, a fully counterbalanced design was not conducted. Although an overall increase in performance was found following QE training, the data suggest this most likely reflects the effects of practice. Consistent with Study 1 (Chapter 3) we found that golfers still experience considerable success with a QE duration less than the prescribed optimal duration. These findings do call into question the underlining mechanisms behind QE and the premise of the assumption that longer is better. Moreover, not every participant did improve their performance following the QE intervention, therefore highlighting the need to move away from group averages and recommendations. Combined with the findings from Study 1 (Chapter 3) it is critical to continue to explore how pertinent QE duration is to performance in highly skilled golfers on an individual participant and trial basis. These findings are required to understand whether it is appropriate to train all golfers based on group norms. To explore if the difference in performance was due to practice effects, another study (Study 2c) has been designed, whereby participants perform two testing sessions one week apart – allowing task order to be fully counterbalanced.

Chapter 5: Study 2b- Exploring neural activity, visual strategy and golf putting performance

This chapter will outline EEG findings captured during study 2a). The findings in Study 2a did suggest QE intervention training did offer a performance benefit in comparison to performance in the control condition. However, examination of performance on a trial by trial basis did allude to individual differences- with not every participant receiving a performance benefit following the intervention and optimal QE duration did not always lead to success. Furthermore, the inherent confounds due to practice effects based on the study design do limit the potency of the performance effects. Therefore, the three main aims of this study are to explore whether firstly there is a relationship between neural activity and Quiet Eye (QE) and secondly if there is a relationship between neural activity, QE and expertise. Thirdly to understand whether neural activity can explain any potential benefits of the QE intervention training by exploring the underpinning mechanism of QE. As we show below, it is challenging to measure neural activity as a function of expertise and QE, however, the findings offer encouragement towards the benefits of a mobile neuroimaging approach for understanding golf putting performance.

5.1 Introduction

QE in golf putting is a simple concept which suggests maintaining a steady vision on the ball prior to initiation of movement action will improve performance (Vickers, 1996). A longer QE duration has been recommended as optimal for golf putting, as research suggest expertise is related to QE duration with highly skilled golfers (handicap less than 4) exhibiting a longer mean QE duration (2.5–3.0 s) in comparison to the shorter mean QE durations (1.0–1.5s) for less skilled golfers (Vickers, 1996). It has been proposed that a longer QE duration allows for more time to pre-programme the movement parameters (Mann et al., 2011; Williams et al., 2002; Vickers 1996). In studies so far in this thesis, the influence of a longer QE duration on performance is unclear. Notably, shorter QE durations have been found to be related to increase in success and the findings from our QE intervention training study in 2a (Chapter 4) did suggest at a group level a QE intervention is beneficial for performance, however when examined beyond a group level, findings revealed not everyone benefited from a QE intervention and trials of optimal QE duration did not always led to performance success. These differences are in line with research that has found individual differences in QE duration exist, both in the duration of QE and in the impact of QE duration on performance (Baker & Wattie, 2016). Currently the reasons for these individual differences are not well understood (Davids & Araújo, 2016). In part, the lack of understanding could be attributed to the majority of research in this area focusing on group differences, using mean values (Lebeau et al., 2016) rather than examining QE duration at an individual participant level or trial level. Therefore, the function of QE duration and whether QE *per se* causes a direct improvement in performance is not clear and a contemporary issue to be addressed (Causer, 2016; Gonzalez et al., 2017; Williams, 2016; Wilson et al., 2016).

The lack of understanding about the function of QE has prompted researchers to propose EEG technologies as a methodology of measuring mechanisms behind QE (Gonzalez et al., 2017; Mann et al., 2011). Accordingly, if a longer QE duration does increase motor preparation in comparison to trials with a shorter QE duration, then there should be a difference reflected within the neural signals (Gonzalez *et al.*, 2017). However, the idea of being able to measure mechanisms and differences in neural processing are promising, these descriptions are vague, and are missing key details such as, the specifics of cognitive processes and region of the brain i.e., motor cortex. If the neural basis, including underlying cognitive processes and regions of the brain that are involved in successful putting can be established alongside understanding QE duration or visual strategies, then together this information can help determine the correlates of superior putting performance and provide the foundation to consistently apply QE findings in the applied domain.

The advance of EEG technology from large equipment which can only be used in a laboratory to small portable battery-operated equipment has allowed for the study of mobile cognition. Mobile cognition can be characterised as the study of cognition in the real world where participants are carrying out behaviour in a dynamic environment. The aim of mobile cognition is to capture brain activity (e.g., EEG) and where appropriate other correlates of behaviour (e.g., eye movements) concurrent to natural behaviours (Ladouce, Donaldson, Dudchenko, & Ietswaart, 2017). This approach allows the researcher to gain understanding of what is happening in the brain to enable the individual to respond and produce behaviour in accordance with their goals (Ladouce et al., 2017). In the context of sport, utilising a mobile cognition approach is essential to overcome the mismatch between the behaviours measured in laboratory settings and behaviours required in real sporting contexts (Park, Fairweather, & Donaldson, 2015).

Therefore, the first aim of this study is to explore whether it is possible to firstly capture mobile EEG and eye tracking data together alongside golf putting performance in a way that does not restrict normal sporting behaviour and maintains high quality EEG signal.

EEG research into sport expertise has found that are differences in neural activity between experts and novices (see Chapter 2, section 2.5). The differences have been found during non-sporting activities during rest (Babiloni et al., 2010) and during sporting performances. For example, an increase in alpha power (8-12 Hz) has been found in experts in comparison to novices in both shooting and archery (for review see Hatfield et al., 2004). Taken together these findings conclude experts are more efficient in their processing in comparison to novices and this has led to the development of the neural efficiency hypothesis (Del Percio, 2009). The neural efficiency hypothesis is considered the most popular way to explain why experts have superior performance over novices in golf putting (Del Percio et al., 2009). The neural efficiency hypothesis is also consistent with Fitts and Ponser (1967) model of skill acquisition which describes a model of learning and expertise in three progressive stages. In each stage, as the level of expertise increases, the level of automaticity in skill execution increases thus reducing the cognitive processing requirements. For example, the first stage; named the ‘cognitive stage’ is associated with novices who, when engaging with the task, use high levels of cognitive effort to carry out effortful processing. The second stage, named the ‘associative stage’, is linked to immediate level performers, and at this stage the person is becoming more efficient in their movement actions and processing. The final phase is the ‘automatic stage’ and is associated with expert performers, who demonstrate automaticity in their movement and processing when carrying out the task and as such do not engage in effortful processing. In this model there are observable differences between the novice and experts in their movement patterns i.e., jerky to smooth and the neural efficiency hypothesis could offer one explanation why there is reduction in cognitive processing.

The neural efficiency hypothesis is also consistent with the efficiency paradox outlined by Mann *et al.* (2016), which outlines why longer QE duration for experts is not appropriate. However, it could be argued there needs to be a new approach which combines the neural, ocular and behavioural responses together into one theory rather than separate isolated theories. Developing a new approach would require a multi-measure approach that combines eye tracking equipment, EEG technologies and performance measures. At this stage only one study has been able to complete this task in shooting (Janelle et al., 2000). In golf putting, three studies have focused on EEG and QE duration (Gallicchio et al., 2018; Gallichio & Ring, 2020; Mann et al., 2011), however, these studies did not use an eye tracker to capture eye behaviour (opting to use EOG) and performance was not measured in Mann *et al.* (2011) and adapted measures of performance (see below) were used in Gallicchio *et al.* (2018) and Gallicchio and Ring (2020).

When calculating Quiet Eye and eye stillness using the horizontal EOG signal a voltage-threshold algorithm was used, however the method of calculation varied between the studies (Gallicchio et al., 2018; Gallichio & Ring, 2020; Mann et al., 2011). Moreover, when using EOG, the researcher cannot account for gaze location and this opens the debate as to whether it is the stillness of the gaze, rather than location of the gaze which is important. There were also differences in the approaches taken to analyse the EEG data and with such limited study in this area, this makes it challenging to draw conclusions at this stage. Mann *et al*. (2011) analysed the EEG via Movement Related Cortical Potentials (MRCPs) and Gallicchio and colleagues analysed EEG data in the frequency domain.

MRCPs were first discovered by Kornhuber and Deecke (1964) when examining changes in the brain before and after voluntary movement. They noticed in the preparation period before a voluntary motor movement, specific cortical activity occurred. It is believed that MRCPs give an insight into the cortical processes involved in the planning and preparation of voluntary motor movement (Shibasaki & Hallett, 2006). The main component studied is the Bereitschaftspotential (BP), roughly translated from German to English, as the ‘readiness potential’ (Deecke & Kornhuber 1978). Using the ERP waveform two phases or components of the BP can be distinguished: “early and late BP” (Shibasaki & Hallet, 2006). The “early BP” (BP1, generated by the pre-supplementary motor area, SMA and lateral premotor cortex bilaterally) begins about 1.5 s before movement onset. The “late BP” (BP2, generated by the primary motor cortex and lateral premotor cortex) characteristed by a steep surface-negative slope begins approximately 400 ms before movement onset. However, when considering previous research and the timings of BP, it is important to acknowledge that equipment used, movement activity i.e., motor task, instructions given, trigger used, plus individual differences within subjects, can impact on precise timing of components

(Colebatch, 2007). For example, Berchicci *et al.* (2012) reported onset of the BP, varied between 3000ms (Klostermann et al., 1994), 1000ms (Moster & Goldberg, 1990), 800ms (Thickbroom & Mastaglia, 1985) and 650ms (Kurtzberg & Vaughan, 1982). Examining the change in amplitude of BP (measured as a function of time) has also been used as measure of motor preparation (Wright et al., 2012). A greater negativity is believed to be associated with pre-motoric task execution facilitates task-related information processing (Freude et al. 1999). However, when studying the BP in shooters, despite their prediction that the trigger pull would be preceded by a more pronounced negative in the elite group, relative to the pre-elite group, Konttinen *et al*, (2000) found this was not the case with pre-elite demonstrating more pronounced negativity in comparison to elite. Similarly, Wright *et al.* (2012) found that after a period of five-week practice (with novice musicians) amplitude declined. The authors interpreted the finding of reduced motor cortex activity during the preparation period in line with the neural efficiency hypothesis. Although it is not clear whether someone can be considered an expert after 5 weeks of practice. To the best of our knowledge currently examining amplitude changes as a function of performance (successful/unsuccessful) in highly skilled athletes has not been completed therefore, future research is warranted.

MRCPs are appropriate for use in golf putting as the task enables the three principles outlined by Colebatch (2007) to be fulfilled as i) the participant is fixated on one point at the point of movement, ii) the participant chooses when they are going to initiate the movement and iii) the lazer trigger used to time stamp the data is linked to initiation of movement. However, despite the suitability only one study has analysed neural activity in golf putting using MRCPs (Mann et al., 2011). In the Mann *et al.* (2011), study, 10 skilled (mean handicap 1.2) and 10 less skilled golfers (mean handicap 11.3) participants putted balls to a 12-ft (i.e., 3.7-m) straight hole. They computed the QE by applying a voltage threshold to the EOG signal and found the more skilled golfers had longer quiet eye durations (around 2.3 s) compared to the less skilled golfers (around 2.1 s). BP was related to QE, with an increase in QE duration related to an increase in BP negativity at specific central regions. More specifically, Mann *et al.* (2011) found significant correlations between QE duration and BP peak amplitude at C3 (r = .3096, p = .026, d = .65), C4 (r = .2874, p = .036, d = .60), and Cz (r = .2901, p

= .035, *d* = .61). Performance differences in MRCPs were not analysed so it is not clear how the change in neural activity was linked to performance or expertise.

In the other studies exploring EEG in golf putting, a different form of analysis has been used, namely, frequency analysis (Gallicchio et al., 2018; Gallichio & Ring, 2020). To conduct frequency analysis the raw EEG signal is decomposed into constituent frequency components (how many cycles occur in one second) and the Fourier transform is applied to provide a power spectrum (Park et al., 2015). When using frequency analysis, Gallicchio and Ring, (2020) found a negative correlation between occipital power (across theta, alpha, beta) for QE durations prior to initiation of the swing (Gallicchio, & Ring, 2020). Furthermore, they found that gaze duration was not related to performance and or skill level. They explained this unexpected finding through their own previous research, whereby an increase in performance was related to an increase in occipital alpha power, thus suggesting reduction in visual processing is more effective for performance (Gallicchio & Ring, 2020). If a reduction of visual processing is more effective for performance, this calls into question the proposed motor preparation hypothesis (*cf.* Vickers, 2007) to explain why QE duration enhances performance and the functionality of QE intervention reinforcing a longer QE duration.

Gallicchio *et al*. studies have helped to develop knowledge of the theoretical underpinnings of QE, but from a representative task design (Brunswik, 1956) and applied perspective, it could be argued both their designs are missing key concepts present in the applied domain. For example, in their first study (Gallicchio et al., 2018), the putting task was a repetitive (60 trials) single putt design (2.4m straight putt), requiring participants to putt the ball on an artificial surface (Turftiles) with an adapted hole using a standardised putter of 90cm in length. The hole was adapted to ensure equal putting success, based on skill level with novices putting in a hole bigger than experts (diameter: 10.8 cm) and half-size for experts (diameter: 5.4 cm), with neither hole size comparable to competitive golf in the applied domain. Furthermore, participants were split into two groups expert and novices based on handicap; participants (10 experts [age: $M = 20.90 \pm 0.74$ years; experience: $M = 11.25 \pm 3.78$ years; handicap: $M = 1.50 \pm 2.32$] and 10 novices [age: $M = 19.00 \pm 0.66$ years; experience: $M = 1.85 \pm 2.49$ years; no formal handicap]). Handicap has been found to be a poor predictor of putting expertise (Carey et al., 2016) and no measure of putting expertise was taken. Moreover, the use of standardised putter, especially with expert golfers is problematic as the putter may be ill fitted based on the varying’ height and putting posture. Additionally, expert golfers typically have their putter professionally fitted to them customising the size, the loft, the grip and markings based on their height, putting posture and preferred specific style of putter. Putting with an unfamiliar putter will change the feel and specific kinematic stroke of the golf putting action.

In the second study, Gallicchio and Ring (2020), again used a single repetitive straight 2m putt set up on an artificial tiled surface (Turftiles; Stimpmeter value: 2.27 m) with 32 participants using a standardised putt. This time however, due to the use of novices, participants were asked to “get the final position of the ball as close as possible to the target”, thereby changing in task and goal directed behaviour. The target in this case was a 6mm diameter adhesive paper marker placed on the putting surface. Additionally, the task was changed from a self-paced task to a guided task as participants were instructed on what behaviour to complete prior to putting and prompted when to putt. For example, prior to each putt participants were asked to stand in a relaxed position and maintain their gaze on a fixation cross placed at eye level on the facing wall (1.5 m away) for 4-5 s, until a 200-ms acoustic tone prompted them to prepare for the putt. In both these studies, the change in task design impacts on the action fidelity and functionality (*cf*. Pinder et al., 2011) of the task. At this stage, due to the limited number of studies and differences in methodologies, no firm conclusions can be drawn from the research into EEG, QE duration and golf putting performance. Subsequently, this present study has been designed to address some of the existing limitations in previous research, in an attempt to develop the knowledge further so that applied recommendations can be made.

The present study has been designed to use an eye tracker to measure QE duration and gaze behaviour to enable the researcher to capture gaze location. To help understand the behaviour in context, time frequency analysis of the EEG data will also be conducted. Time frequency analysis combines frequency information with temporal information to allow the researcher to make inferences about neural oscillations, with particular reference to a time locked event (Cohen, 2017). If the goal is to investigate neural information in a sequenced approach i.e., seconds prior to post a specific event, then time frequency analysis is thought to be best suited for this type of analysis as it offers temporally precise analysis with millisecond resolution (Cohen, 2011). It is hoped that time frequency analysis will help to provide understanding towards the basic mechanisms which underlie sporting performance and help to differentiate if there are any differences between successful and unsuccessful performance, for both QE instruction and control putts, just prior to initiating the motor action. So far, research utilising EEG methodologies in golf putting to measure expertise is limited, nevertheless the early findings are encouraging as researchers have found expertise based differences in EEG signals during preparing time, downswing between the successful and unsuccessful putts (Ji, Wang, Zheng, Hua, & Zhang, 2019). However, at present, there is no consensus in the findings regarding whether increases or decreases in power across alpha, theta, and beta including the sensorimotor rhythm (SMR:13- to 15 Hz) lead to successful performance in expert golfers (Tables 4 and 5 in Chapter 2). For example, studies have reported both an increase in alpha power (Baumesiter, Reinecke, Liesen & Weiss, 2008; Cooke et al., 2014) and a decrease in alpha power (Babiloni et al., 2008, Cooke et al., 2014; 2015) are linked to successful performance when testing both expert and novice participants.

Theta, in particular frontal midline (Fmθ), has also been linked to superior golf putting performance (Kao et al., 2013; Reinecke et al., 2011). Kao *et al.* (2013), found theta power was significantly lower for the 15 best putts, in comparison to 15 worst putts at FZ, CZ, PZ, OZ, with 18 skilled golfers (average of 10.8 ± 5.4 years) of competitive experience at national level in Taiwan using an artificial surface, with repetitive putts task design on a sloped green using a modified hole (Kao, Huang, & Hung, 2013). In contrast, Reinecke *et al.* (2011) found there was an increase in theta power at F3 for experts in both the laboratory and field condition, however, even though both studies used golf putting; the task design, and analysis processes including choice of electrodes and epoch were different making a direct comparison difficult. In support of Reinecke *et al.* (2011) findings from a broader motor control context suggest an increase in frontal midline theta power has been linked to expert performers (Doppelmayer, 2009) and increased cognitive, visuomotor and sensorimotor control (Baumeister et al., 2008; Slobounov et al., 2000). An increase in theta power is believed to represent sustained attention (Sauseng et al., 2007) with particular focus on planning and initiation of motor control (Wyble et al., 2004). At this stage, in relation to golf putting, further investigation is warranted to examine how theta power changes through the pre shot period.

The sensorimotor rhythm (SMR:13- to 15 Hz oscillation) has been described as an indicator of cortical activation, reflecting automatic process-related attention (Mann et al., 1996). The one study which has examined SMR in golf putting found SMR was linked to improvements in golf putting performance (Cheng et al., 2015). Cheng *et al.* (2015), recruited fourteen male and two female elite golfers (mean handicap = 0 ± 3.90) to take part in an intervention study with a control group to explore if increase SMR activity could improve performance. To work out individual putt distances consistent with Arns *et al.* (2008), participants were asked to initially putt from a putt distance of 3 m to a hole of 10.8 cm in diameter on an artificial surface. The putt distance was reduced until the participant could hole 50% of their putts, however, final putt distance for participants was not stated. After the intervention performance improvements were recorded for the intervention group but not the control group. The authors concluded greater SMR activity could be linked to improved performance through improved attention processing. However, at this stage it is unclear whether the putt distances were different for the control or intervention group. Therefore, this limits the applied application of the findings and accordingly our study hopes to gain further understanding of how SMR is related to performance.

Differences in the methodologies, for example, electrodes chosen, type of EEG analysis, variation in epoch duration, baseline duration (if stated) and task design factors such as use of standardised putter, change in the hole size and putt surface (see Tables 4 and 5, Chapter 2) across the studies has made it difficult to compare the studies. There have also been differences in how the frequency alpha has been analysed in the golf putting literature, with alpha being conceptualised as a range of different measures, namely, peak alpha frequency (with some research e.g., Ring *et al.*, 2015 only analysing high alpha power only) and spectral power density (dB). Therefore our study has been designed to allow participants to use their own putter and the participants have been asked to putt to five locations in a random order on a comparable surfacer. It is acknowledged, although that this design is far for being completely representative as key perceptual variables found when putting outside or in an indoor golf centre are missing and due to the high trial numbers. To enable enough trials, there is a high volume, much greater than typically taken per round and all putts will be from 8ft in distance and straight (putt type), therefore limiting the representative nature, however, the putt position will vary in each trial. In EEG sports research, it is not clear at this stage if the repetitive nature cannot be reduced due to the number of trials required for data analysis for time frequency analysis (Cohen, 2017). However, the aim of this study is to gain an understanding of the number of trials required to maintain a high-quality signal. Putting expertise will also be measured beyond handicap to help provide a more reliable predictor of putting expertise. Overall, it is hypothesised that there will be a relationship between brain activity and QE and expert based differences will be found in the frequency bands and MRCPs.

The key research questions are:

1. Is there a relationship between EEG brain activity and Quiet Eye?
2. Are there measurable neural signals that can be identified for putts taken after the QE intervention and do they differ from control putts taken prior to the intervention?
3. Are there any expertise based differences in the frequency bands, theta, alpha, SMR, beta?
4. Are there any expertise based differences in MRCPs?

5.2 Methodology

5.2.1 Participants

Twenty-eight participants (20 males, 8 females) were all right-handed, right eye dominant and had normal or corrected vision. Mean age was 24.2 years ± 6.4 and average handicap +1.7 ± 6.4. Mean years played golf was 12.8 years ± 5.69, average weekly practice was 15.5 hours ± 11.5, average putts per round was 31.3 ± 2.84, average green in regulation was 56.2% ± 10.1. Average scored from 6ft straight was 85% ± 21.1.

5.2.2 Procedure

Ethical approval was granted by the General University Ethics Panel (GUEP) at the University of Stirling. All procedures were in accordance with the Declaration of Helsinki ethical principles for conducting research with human participants. The lead researcher contacted the National Governing Body and University of Stirling Performance Director for golf and local golf clubs for permission to speak to players matching the eligibility criterion, to determine interest in participating in the study. The lead researcher then met interested players to explain the study requirements and related information. Following this meeting, players were asked to confirm involvement in the study by returning a signed copy of the informed consent sheet and demographic information to the lead researcher. Players were made aware that participation was not a requirement, it was voluntary without obligation and participation had no influence on training and selection. There was no coercion to participate from the coaches or the lead researcher. All participation was voluntary and non-disclosure, consent for participation was obtained prior to the participant starting testing.

Participants attended the testing sessions individually and an ASL mobile eye tracker and EEG equipment (eego**™sports,** ANT-Neuro, Enschede, The Netherlands) was fitted by the lead researcher. EEGO sport is a mobile EEG system that has 32 Ag/AgCl electrodes within the cap, which is connected to a battery powered amplifier stored in a specially designed rucksack to enable the participant to be free to complete their normal movement routines. Participants used their own putter (fitted by golf professional prior to the study to ensure consistency for all participants) and Srixon AD333 Tour golf balls were provided. Participants were given an opportunity to ask any further questions prior to commencing the experiment. Participants were asked not to discuss the experiment outside of the study session.

5.2.3 EEG recording

EEG data was recorded from 32 Ag/AgCl electrodes connected to a portable amplifier (ANT-neuro, Enschede, The Netherlands), with a sampling rate of 500 Hz, a 0.016–250 Hz bandpass filter and notch filter set at 50 Hz. Electrodes (FP1, FPz, FP2, F7, F3, Fz, F4, F8, FC5, FC1, FC2, FC6, M1, T7, C3, Cz, C4, T8, M2, CP5, CP1, CP2, CP6, P7, P3, Pz, P4, P8, POz, O1, Oz, O2) were positioned according to the International 10–20 system (Jasper, 1958). Electrode AFz served as the ground and CPz as a common reference site. Electrode impedance was measured prior to each recording session and each channel was maintained below 10 kΩ using electrode gel. Post testing session an average reference was used. Timestamping of events was used through a laser trigger sent when the putter 'is no longer in the line of the beam' to mark the initiation of the backswing and then 'when the putter is back in line with the beam' to mark contact with the ball (Figure 21). To keep it consistent with other golf putting studies contact was chosen as the trigger point, however, this may be problematic when measuring movement related cortical potentials. For the power spectral density analysis and the time frequency analysis, *a priori* frequency bands were selected based on the wider neuroscience literature and sporting literature; Theta (4-7 Hz), Alpha (8-12 Hz), SMR (13-15 Hz) and Beta (15-30 Hz).

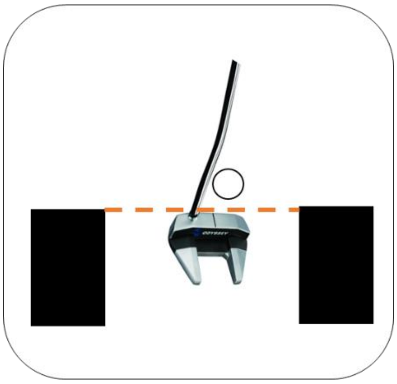


Figure 21. Trigger setup to send a time stamp to the EEG raw data to mark the initiation of the back swing and contact.

5.2.4 Testing Procedure

The procedure is outlined in Study 2a.

5.2.5 Measures

The measures are outlined in Study 2a, however, this study focuses on the addition of measuring EEG data. We focus on the more common measure of power (measured across multiple frequency bands). The spectral data was normalised using a relative change baseline of 500ms. Frequency will be reported as relative power (% change) based on the *a priori* selected frequency bands. For the time frequency analysis, the same 500ms baseline will be applied by dividing power within the area of interest by the equivalent power during the baseline and in this case scaled as a percentage so the change relative to the baseline in the two conditions can be explored at selected electrodes. It is also of interest to explore whether there are any changes in the seconds leading up to the contact (0ms) or post putt relative to baseline, so the data will be spilt into 500ms second epochs, namely -2500ms to -2000ms, -2000ms to -1500ms, -1500ms to -1000ms, -1000ms to -500ms, -500ms to 0ms and 0ms to 500ms.

For the MRCPs analysis, following the literature (e.g., Berchicci et al., 2012), we considered the Cz site for the analysis of amplitude and onset of the BP. The BP amplitude was measured as the mean amplitude at the peak (±100ms). BPs tended to reach their maximum at -650ms (-750 to -550ms) before the contact point (0ms). In this study, similar to Verleger *et al*. (2016) who used the key press rather than onset of preceding muscle activation, our time points are referenced to the contact of ball and putter rather than the onset of preceding muscle activation.

5.2.6 Data Analysis

The analysis for the performance and visual measures are outlined in Study 2a. This section will explore the analysis conducted on the EEG data. EEG data was analysed using the EEGLAB (Delorme & Makeig, 2004) open source toolbox and bespoke MATLAB scripts (version R2019b 8.4.0.150421, The MathWorks Inc.) based on the specific research aims and questions for the time frequency data analysis. When completing the analysis in EEGLAB, the first stage of data processing was visual inspection of the continuous data to allow any sections of 'noisy' data to be manually rejected by the researcher. A Finite Impulse Response (FIR) band-pass filter ranging from 1 to 30 Hz to the continuous data (filter order: 16500, −6dB cut-off) was then applied to the data. An extended infomax Semi Independent Component Analysis (ICA; Bell & Sejnowski, 1995) was conducted to identify any artifacts. The technique of dipole fitting to assess the source estimates of the independent component was used to help ensure all noisy artifacts were rejected. Furthermore, identified artifacts, were then subjected to an additional method of Semi Automatic Selection of Independent Components for Artifact correction using the SASICA toolbox (Chaumon, Bishop, & Busch, 2014). The SASICA toolbox has been developed with the explicit aim of improving accuracy of selecting which components to reject. Firstly, preliminary data checks using a series paired *t*-tests were completed to assess the quality of the data signal by comparing the period of interest and baseline activity, and data quality as a function of performance. Furthermore, paired *t*-tests were also conducted to compare the differences in the number of components removed after pre- processing of the data to ensure there are no differences in components removed based on performance.

Following the preliminary checks of the data, a 2 (Performance: Hit, Miss) * 3 (Frequency: Theta, Alpha, Beta) * 15 (Electrodes: F3, Fz, F4, FC1, FC2, C3, Cz, C4, CP1, CP2, P3, Pz, P4, POz, Oz) within design repeated measures ANOVA was conducted. Then consistent with our aims to understand performance any significant interactions involving performance were to be followed up by repeated measures ANOVA examining the pattern of effects over time, or between electrodes (e.g., examining each time window using ANOVA with factors of performance and region or electrode as appropriate). All analyses were caried out using a significance threshold of $p < 0.05$, and any significant effects involving performance were followed up using paired sample *t*-tests (including Bonferroni correction for multiple comparisons where appropriate) to confirm whether performance related differences were reliable.

MRCPs were analysed using the BrainVision™ system (BrainProducts GmbH, Munich, Germany), with 30 electrodes mounted according to the 10–20 International System (Jasper, 1958). The processing pipeline was consistent with previous MRCPs research outlined in Berchicci *et al.* (2012) and Perri *et al.* (2014). All electrodes were referenced to average reference. The EEG was digitized at 250 Hz, band-pass filter 0.01–80 Hz including a 50 Hz notch-filter was applied. Visual inspection of the continuous data was undertaken and any 'noisy' data was manually rejected by the researcher. Using the inbuilt ICA function, an ICA followed by Artefact rejection (amplitude threshold of ±100µV) was performed before splitting the data in epochs. Epochs were from -3000ms to +100ms in duration and a baseline was applied 3000-2500ms. To explore differences between average hits – average miss *t*-test(s) will be conducted for the whole epoch. Paired *t*-test were conducted to compare differences in mean amplitude as a function of performance.

5.3 Results

The analysis of the QE and performance data is outlined in Study 2a. This chapter will focus on the EEG results.

5.3.1 EEG Paradigm

The paradigm (Figure 22) explored was a 3.5 second epoch capturing -2500ms pre shot and +500ms post shot. Only 500ms was captured post shot as pilot testing revealed participants moved after this time to see the outcome of their putt so there were too many movement artifacts after +500ms. A 500ms baseline at -300ms to -2500ms was used.

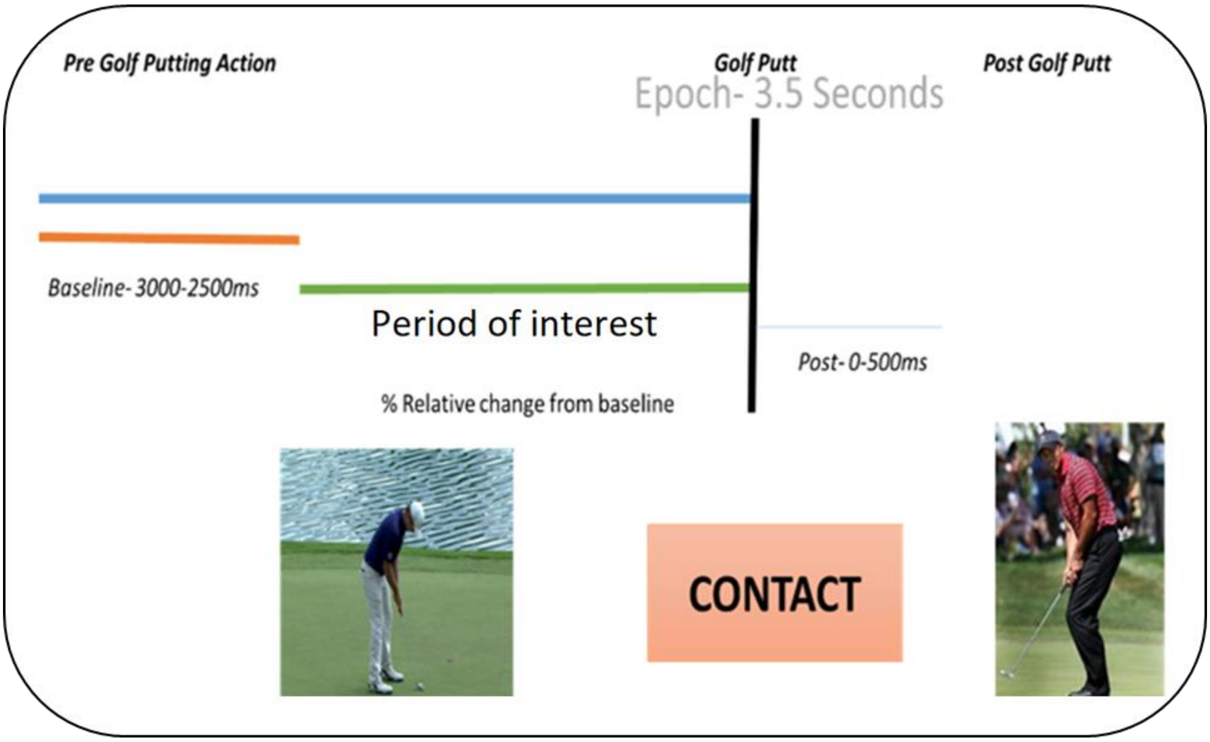


Figure 22. Schematic of the Paradigm.

5.3.2 Analysis of EEG Data Quality

Seven participants were removed due to poor data quality which could be attributed to movement artifacts. Following further checks on data quality (outlined in the methods section above); 21 participants with a total of 1834 hits and 639 miss trials, with an average of 87 trials ± 14 for hits and 39 trials ± 15 miss per participant were retained. Following the data processing based on Cohen's (2016) recommendation of a minimum of 50 trials per condition per participant and at least 20 participants, there were not enough trials per participant across the four conditions (QE hits, QE Miss, Control Hit, Control Miss) to confidently assure quality of signal and the results. Subsequently, it was not possible to complete a direct comparison pre and post QE intervention. In addition, there were also insufficient trials to complete an analysis whereby QE hits/miss are compared to No QE hits/miss, mainly due to the low number of No QE trials once split into hits and miss. Collectively, therefore we can only link timings of mean QE duration onset to the time frequency data, and because of this indirect approach cannot infer causality. Furthermore, when considering the trial numbers of successful shots in comparison to unsuccessful shots, it was not possible to match the trial numbers across the two conditions, due to the design of the study where participants completed a set number of putts. When the trials are not matched there is a concern unequal trial numbers can lead to differences in signal noise and quality between the conditions and ultimately can lead to misinterpretation of the findings (Cohen, 2016). To assess the signal quality and the differences in fluctuations in the signal, RMS (i.e., the arithmetic mean of the squares of a set of values) was calculated to determine any deviation in signal quality as it can be applied to identify any variation in a signal. RMS was applied to all electrodes for both conditions i.e., hit and miss for the epoch trials (including baseline).

To calculate RMS each trial was averaged and then an overall average was created for each condition separately (Cohen, 2017). There was a mean difference of 0.29 ± 2.046 between the conditions (hit/miss), so the RMS was relatively consistent for hits and misses regardless of trial number differences. A paired *t*-test was conducted to compare differences in signal quality between the hit and miss epoch trials and the findings revealed there were no differences in RMS between the two conditions [$t_{(19)}$ = 0.652, p = 0.522]. However, as shown in Figure 23, two participants RMS was higher than the average for the other 19, so they were removed from the EEG data analysis. Taken together, the findings suggest the unmatched trial count across the two conditions, (more hits than misses), did not lead to differences in the signal quality meaning the analysis comparing hits vs. miss can be conducted.

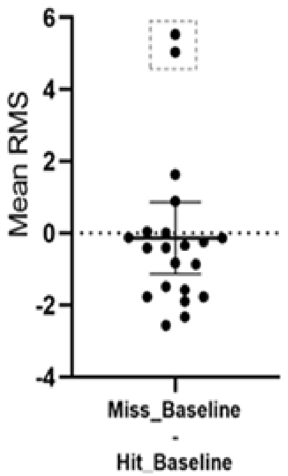


Figure 23. Difference in average RMS for hit epoch in comparison to miss epoch (miss- hit) with 95% CI. Each circle dot represents a participant. Two participants in the square dashed line box have a higher RMS in comparison to the average RMS for the cohort so have been removed.

RMS was also applied to the baseline period (-3000ms to -2500ms) to explore if there were any differences at baseline. If at baseline, no differences exist it can be assumed that any differences during the task (area of interest) are related to differences in neural activity provoked by the task and not due to differences at baseline. A comparison of mean differences in RMS of the signal for the two conditions (hits vs.

misses) revealed the two conditions were similar, 0.13 ± 2.137. The analysis of the paired *t*-test revealed no difference, [$t_{(19)} = 0.288$, $p = 0.776$] in RMS between the two baseline conditions (hits in comparison to miss). As shown in Figure 24, two participants' RMS were higher than the average for the other 19, so they were removed from the EEG data analysis. These two participants were the same two participants who had higher RMS in total epoch above. The findings suggest the baseline was appropriately applied and if any differences are found in the neural activity in later analysis, these differences cannot be attributed to differences at baseline.

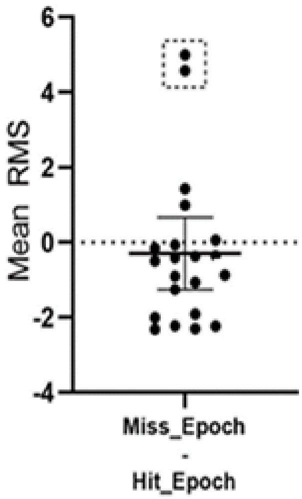


Figure 24. Difference in average RMS for hit baseline in comparison to miss baseline (miss- hit) with 95% CI. Each circle dot represents a participant. Two participants in the square dashed line box have a higher RMS in comparison to the average RMS for the cohort so have been removed.

5.3.3 Independent Component Analysis

On average there were 15 ± 3 components rejected across all the conditions. When comparing if there was a difference in the rejected components between the two conditions (hit/miss) there was a mean difference of 0.105 components ± 0.65. A paired *t*-test revealed no difference in the number of independent components rejected between conditions [$t_{(18)} = 0.6975$, $p = 0.4944$].

5.3.4 EEG Analysis

A range of analyses (spectral power: including time frequency and MRCPs) have been chosen to help develop a greater understanding due to lack of consistency with current findings in golf putting (see Tables 4 and 5 in Chapter 2). Firstly before, conducting the analysis, a check of activity in the baseline period will be conducted to ensure that baseline was appropriate.

5.3.4.1 Baseline

As outlined in the EEG paradigm above, the baseline period was -3000ms to -2500ms, the baseline was chosen to match the timings of the pre-shot routine and motor activity. As shown in Figure 25, there were no differences in neural activity in hits vs misses during the baseline period. This provides support that we appropriately applied the baseline and any changes found in the area of interest (-2500ms to +500ms) were not due to changes present at baseline.

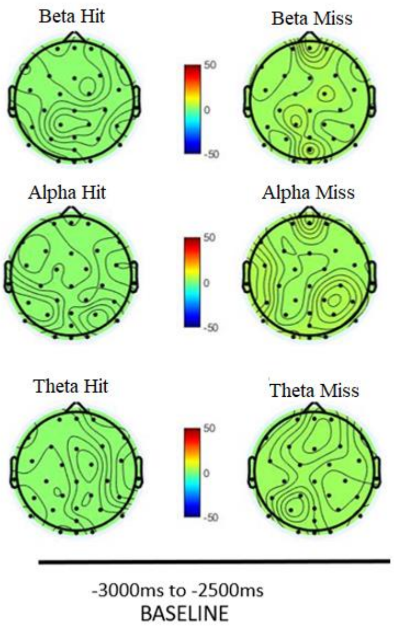


Figure 25. Scalp topographies showing the similar power (percentage change) at baseline between the conditions (hits vs. miss) at all electrodes, showing no differences in baseline power.

5.3.4.2 Spectral Power

To analyse spectral power, relative power (%) from baseline for the whole epoch for hits in comparison to misses was conducted using a 2 (Performance) * 3 (Frequency) * 15 (Electrode) within design repeated measures ANOVA was conducted. The analysis revealed the three-way interaction for Performance * Frequency * Electrode was significant [$F_{(28,504)} = 1.629$, $p = 0.023$, $\eta^2 = 0.006$]. The two-way interaction for Performance * Electrode ($F_{(14,252)} = 2.334$, $p = 0.005$, $\eta^2 = 0.013$) was significant and there was a trend for two-way interaction for Performance * Frequency ($F_{(2,36)} = 2.502$, $p = 0.096$, $\eta^2 = 0.016$). No main effects were significant ($p < 0.005$). Taken together, these findings suggest there are changes in the power and neural activity as a function of performance, providing the basis for a more targeted analysis to be completed in the sections below.

To help guide the targeted analysis, based on the above interaction, a time frequency plot was created to visually inspect the data (Figure 26). The time-frequency plots (including all electrodes and the frequencies of interest (3-30 Hz) based upon on previous literature outlined in Chapter 2) suggest that there are marked changes in brain activity for both successful and unsuccessful performance. Notably in the final second prior to contact (time window -1000 to -0ms), there is a trend of increasing power at 8-12Hz for the hits from -1000ms to -0ms (point of contact) and this increase in power is not present in misses (as reflected in difference percentage change plot). This pattern is also present in all three regions (frontal, central and parietal) as illustrated in Figure 27. In contrast, misses do not have a clear pattern of activity during this time window, with short burst of increase and decrease of activity (the yellow/red colour indicates an increase, and the blue colour is representative of a decrease of power). The greatest difference in power between hits and miss present at -1000 to -500ms time window and this is illustrated in the black box in the difference plot (Figure 26). Additionally, from the time frequency plot there also looks to be differences in power between hits and misses in the pre-shot preparation period at 13-30Hz. As seen in time frequency plot for hits (see black box in the hits plot in Figure 26) there is a decrease in power for the hits at -1700 to -900ms, however, the decrease in power in misses (see black box in the miss plot) in the same frequencies range happens later and for less time (-1000 to -600ms). To explore these differences in more detail, scalp topographies were created to visually inspect the data to explore changes over time at specific electrodes/regions within each frequency to enable a targeted approach to statistical analysis.

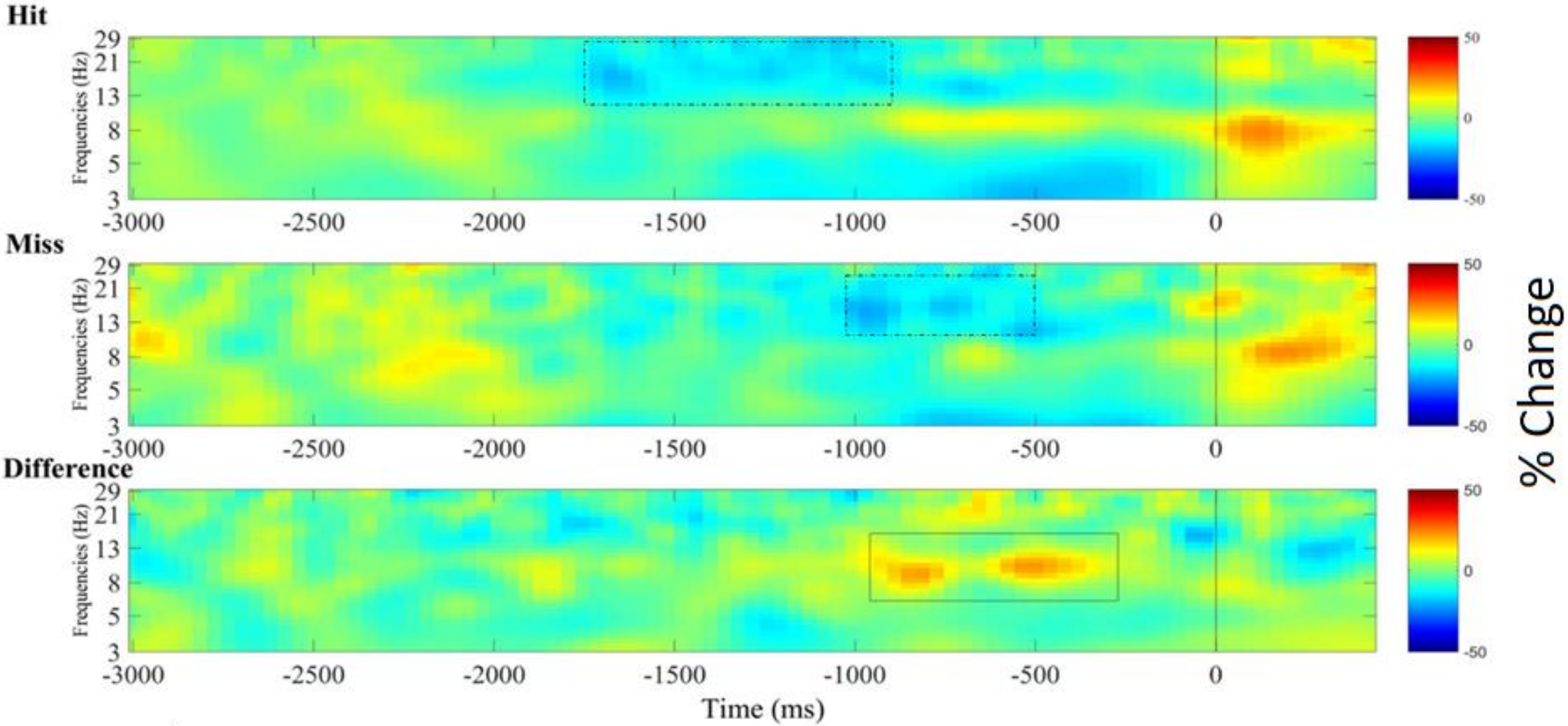


Figure 26. A comparison of the difference in percentage change of power across all electrodes as represented by time (pre and post golf putting action, whole epoch: -3000ms and +50mms) with Oms representing when the putter made contact with the ball and frequencies (3-30 Hz: theta, alpha, beta). The first plot represents hits, the second plot represents misses and three plot represents the difference between hits – misses. The red colour represents an increase of power (percentage change) and the blue colour represents a decrease in power (percentage change). The largest difference is an increase in alpha at 1000ms to -300ms time period as indicated by the black square box on the difference plot.

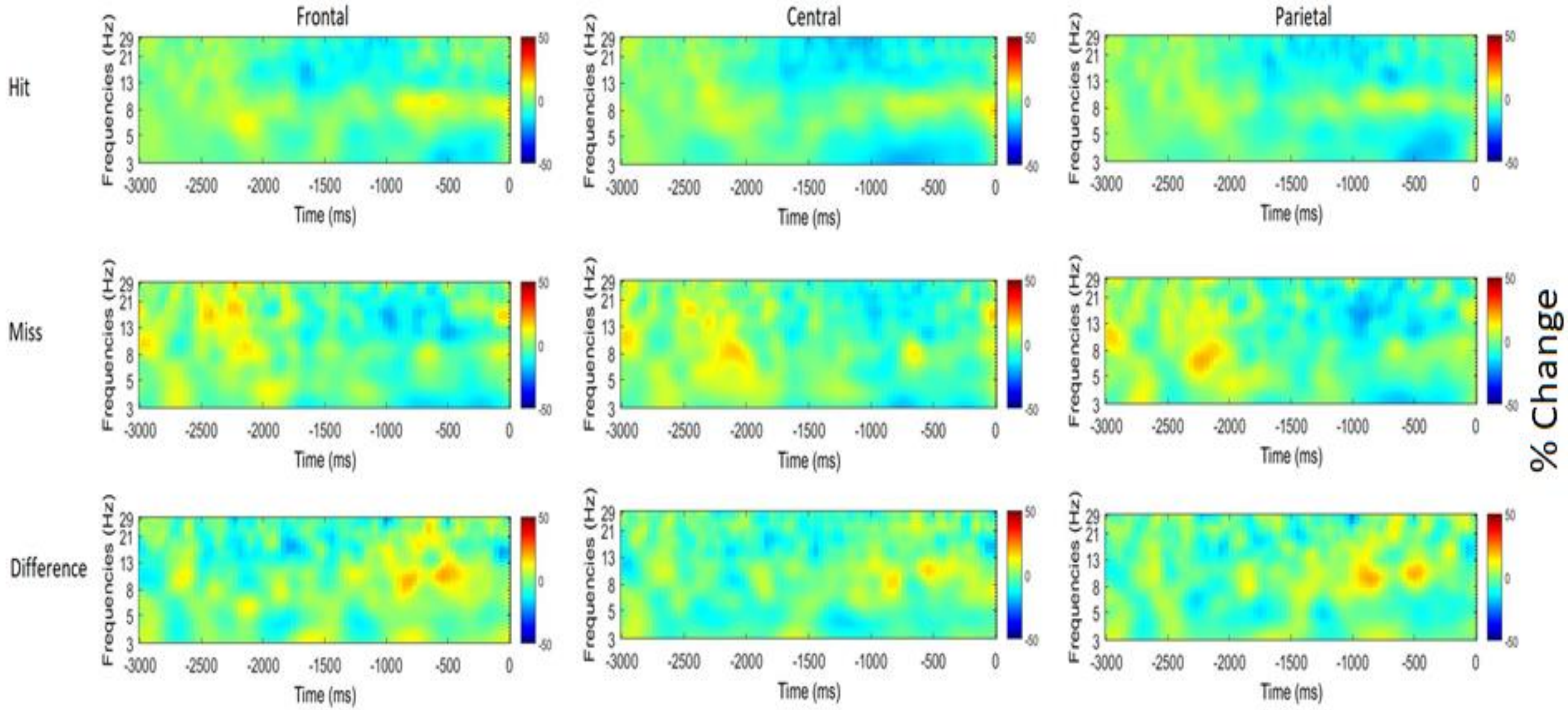


Figure 27. A comparison of the difference in percentage change of power across regions : frontal (left plot, F3, Fz, F4), central (middle plot, C3, Cz, C4) and parietal (right plot, P3, Pz, P4) as represented by time (pre-golf putting action: -3000ms -0mms) with Oms representing when the putter made contact with the ball and frequencies (3- 30 Hz: theta, alpha, beta). The plots on the top row represents hits, the middle row represents misses and bottom row represents the difference between hits – misses. The red colour represents an increase of power (percentage change) and the blue colour represents a decrease in power (percentage change). The largest difference is an increase in alpha at 1000ms to -0ms time period for the hits, in all three regions.

Alpha Oscillations

To explore if there is a difference in power based on hits and misses in alpha (8-12 Hz) region, firstly we used the time frequency plot shown in Figure 26. The plot indicated the largest difference in power based on hits and misses in alpha (8-12 Hz) region, was at two time points (-1000ms to -500ms and 500 to 0ms). Therefore, in order to visually inspect the data, scalp maps (Figure 28) were created to be able to target electrodes for statistical testing.

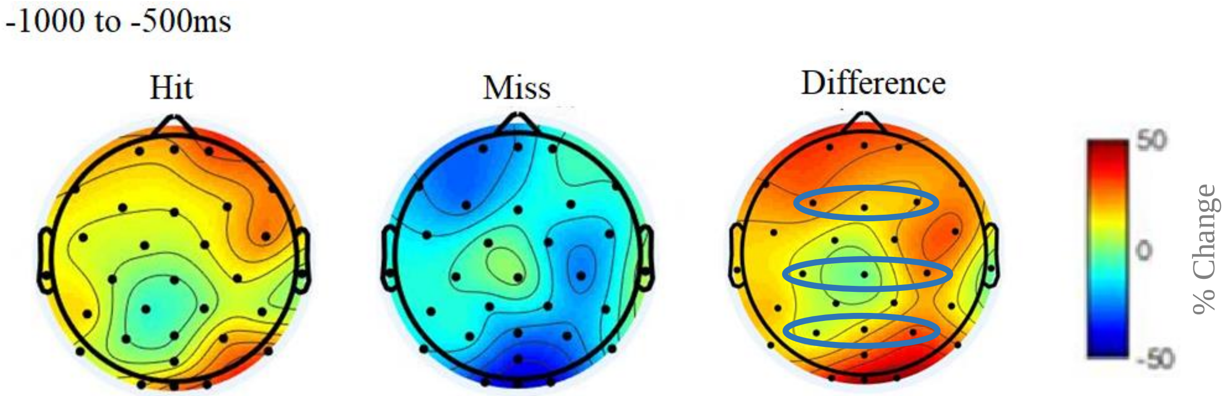
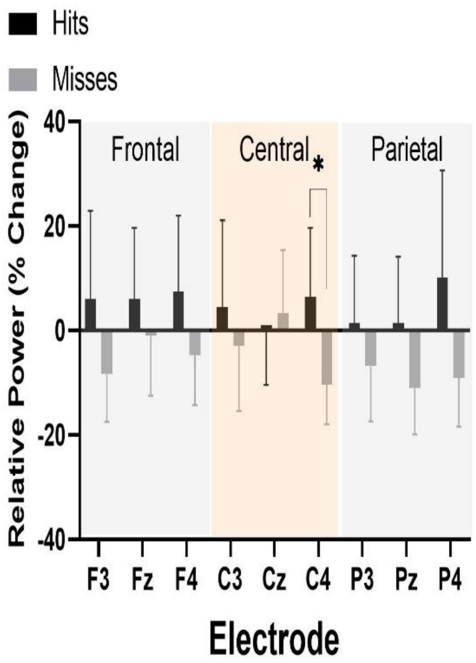


Figure 28. Scalp topographies representing alpha activity (8-12Hz) for successful and unsuccessful performance at the time window -1000 to -500ms. The scaling represents the relative power change (%) from baseline with red indicating an increase and blue indicating a decrease. The top circle on the difference scalp plot indicates frontal electrodes (from left to right F3, Fz, F4). The middle line circle indicates central electrodes (from left to right C3, Cz, C4). Finally the circle towards the bottom of the scalp plot indicates parietal electrodes (from left to right P3,Pz, P4).

As seen in the scalp topographic maps (Figure 28), there is an increase in relative power (%) underlying successful performance at frontal electrodes and a decrease in relative power (%) underlying unsuccessful performances at parietal electrodes. At central electrodes there does seem to a pattern whereby there is an increase in activity, especially on the right hand side (C4) for hits and a decrease in activity, especially on the right hand side for misses (C4). To explore these differences in the frontal, central and parietal regions at the time point of interest (-1000ms to -500ms) a within repeated measures ANOVA with factors of Performance (2: hit, miss) * Electrode (9: F3, Fz, F4, C3, Cz, C4, P3, Pz, P4) was conducted. There was a significant main effect for Performance ($F_{(1,20)} = 3.840$, $p = 0.05$, $\eta^2 = 0.075$) and a significant interaction for Performance * Electrode, ($F_{(3.671,\ 73.424)} = 2.049$, $p = 0.04$, $\eta^2 = 0.028$). The significant interaction between Performance * Electrode is illustrated in Figure 29. At all electrodes there was an increase in alpha power for hits and a decrease in power for misses (with the exception of Cz where there was a relative increase in alpha power for misses), with the greatest differences being observed at C4 and P4 electrodes. It must be noted, however, there is only a significant difference in power based on performance after Bonferroni correction at the electrode C4 (see Figure 29).



Hits - Misses Comparison	Mean Diff.	95.00% CI of diff.	Adjusted P Value	Sig.
F3	14.45	-9.177 to 38.08	0.4934	ns
Fz	7.102	-11.36 to 25.57	0.9226	ns
F4	12.13	-7.870 to 32.14	0.504	ns
C3	7.286	-17.87 to 32.44	0.9865	ns
Cz	-3.561	-18.13 to 11.00	0.9959	ns
C4	16.76	1.782 to 31.73	0.0218	*
P3	8.295	-17.93 to 34.51	0.9759	ns
Pz	12.36	-7.351 to 32.08	0.4607	ns
P4	19.21	-7.261 to 45.69	0.2813	ns

Figure 29. Relative change from power (%) from baseline at -1000 to -500ms for alpha activity (8-12 Hz) at selected electrodes for successful and unsuccessful putts. There was a significant difference in activity at the electrode C4 with an increase in activity for successful putts in comparison to misses.

We are cognizant of the critique we have been making towards the evidence base in the QE literature for only focusing on group analysis especially as expertise is associated with individual process (Dicks et al., 2009), so we wanted to explore the significant group finding for C4 on an individual basis. Results revealed individual differences and four main patterns could be seen in the data (Figure 30). Five participants demonstrated a decrease across all frequency bands of hits but not misses. Nine participants demonstrated an increase in theta and alpha for hits and an increase in all frequency bands for misses. Two participants showed mainly no change from baseline power across the frequency bands for hits and a decrease in alpha from -1000ms to -500ms for misses. The final three participants exhibited a unique pattern, and they are present in the figure below.Taken together these findings suggest, analysing data on an individual level is important to be able to make applied recommendations. Analysing EEG on an individual basis will present considerable challenges and will require a longitudinal design.

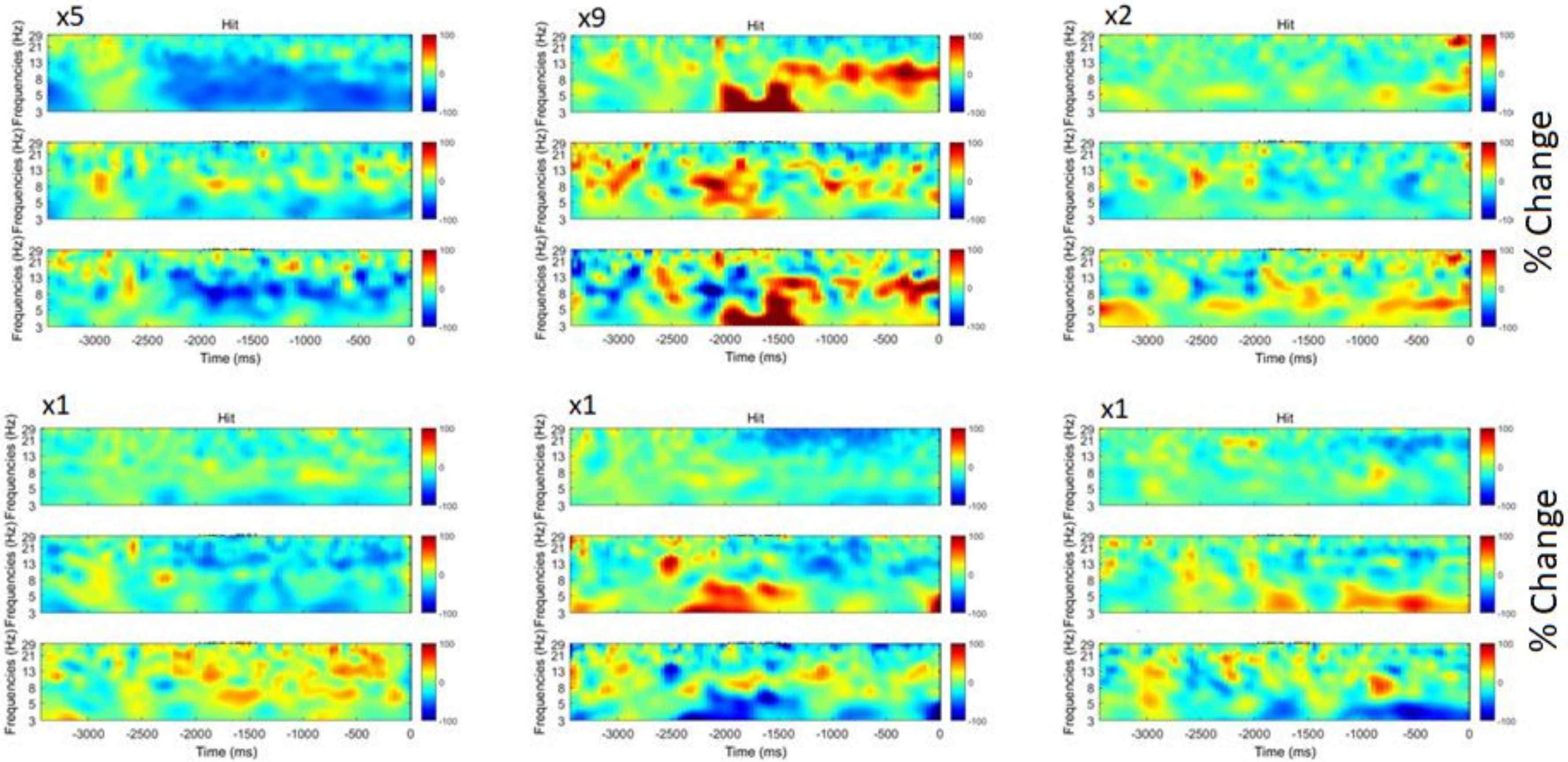


Figure 30. Visualisation for each participant in the analysis of the difference in percentage change of power for hits, miss and difference (hits – miss) at C4 as represented by time (pre and post golf putting action, whole epoch: -3000ms and +50mms) with Oms representing when the putter made contact with the ball and frequencies (3- 30Hz: theta, alpha, beta). Sixteen participants can be split into three distinct patterns as shown on the top row of the figure; decrease indicated by the blue colour, increase indicated by the red colour and no change indicated by the green colour. Three participants show unique patterns shown on the bottom row of the figure. Scaling is 100% to highlight differences more clearly.

-500ms to 0ms

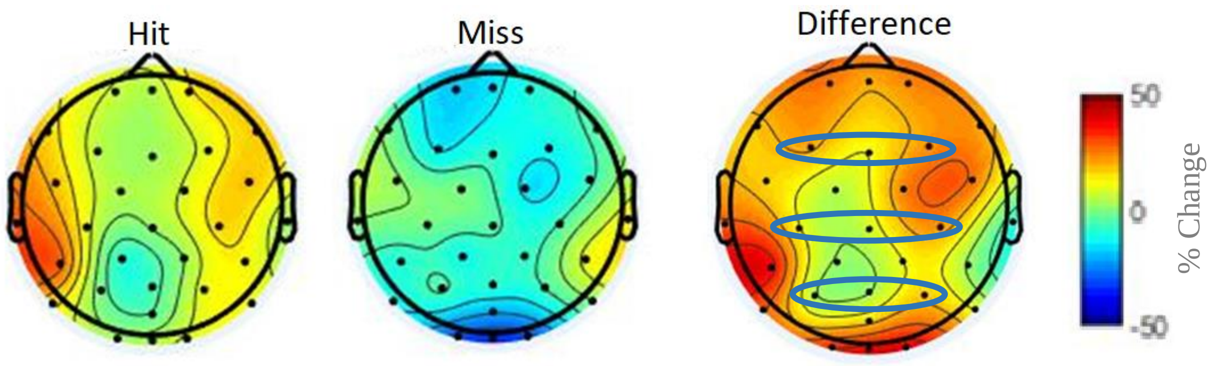


Figure 31. Scalp topographies representing alpha activity (8-12Hz) for successful and unsuccessful performance at the time window -500 to 0ms . The scaling represents the relative power change (%) from baseline with red indicating an increase and blue indicating a decrease. There is a greater increase in activity for successful putts in comparison to unsuccessful putts. The top circle on the difference scalp plot indicates frontal electrodes (from left to right F3, Fz, F4). The middle line circle indicates central electrodes (from left to right C3, Cz, C4). Finally the circle towards the bottom of the scalp plot indicates parietal electrodes (from left to right P3,Pz, P4).

As seen in the scalp topographic maps (Figure 31), there is a pattern of an increase in alpha activity underlying successful performance at frontal electrodes (Fz) and a decrease of alpha activity underlying unsuccessful performances at parietal electrodes. At the central electrodes (C3 and C4) there does seem to a pattern whereby there is an increase in activity for hits and a decrease in activity for misses. To explore these differences in the frontal, central and parietal regions at the time point of interest (-1000ms to -500ms) a within repeated measures ANOVA with factors of Performance (2: hit, miss) * Electrode (9: F3, Fz, F4, C3, Cz, C4, P3, Pz, P4) was conducted. The was no interaction between Performance * Electrode ($F_{(3.834, 72.389)}$ = 0.410, p = 0.793, η^2 = 0.007) or main effect for Performance ($F_{(1,19)}$ = 1.384, p = 0.254, η^2 = 0.023).

Theta Oscillations

To explore if there is a difference in power based on hits and misses in theta (4-7 Hz) region, throughout the pre-shot period (-2500 to 0ms) firstly, scalp topography maps were produced in order to visually inspect the data to be able to target electrodes for statistical testing.

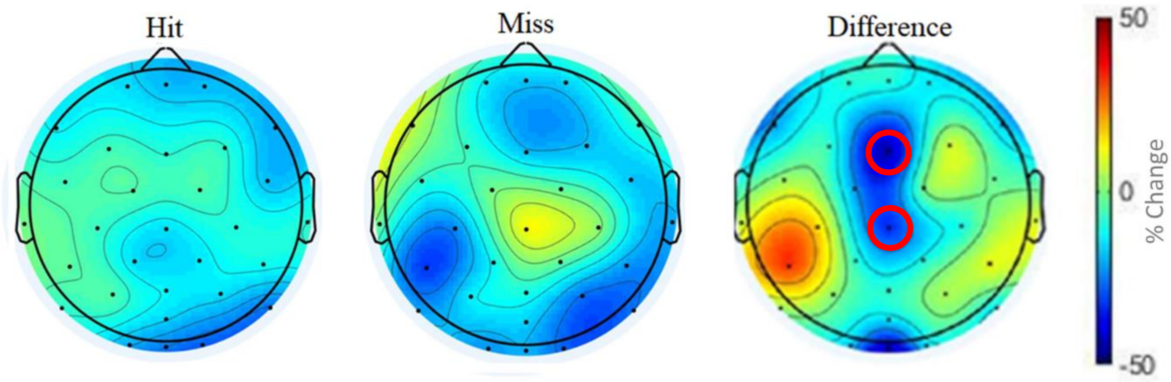


Figure 32. Scalp topographic map representing theta (3-7Hz) activity for successful and unsuccessful performances across the pre shot period -2500ms to 0ms after baseline correction. The scaling represents the relative change in power (%) from baseline with the blue colour indicating a decrease between successful putts in comparison to misses in the mid frontal region. Fz electrode represented by the higher red circle and Cz is the lower electrode represented by the dashed circle.

The scalp topography plots indicated differences in power at Fz and Cz within the whole epoch (Figure 32). To explore this impression further and to see if the difference was significant statistical testing was conducted. Exploring these differences at different time windows throughout the pre-preparation is important as the time frequency plot (Figure 26) indicated that power decreases over the preparation time and that there were changes in activity within the whole epoch. With these considerations in mind a repeated measure ANOVA was conducted for Time (5: -2500 to -2000ms, -2000 to 1500ms, - 1500ms to -1000ms, -1000 to -500ms and -500 to 0ms) * Performance (2: Hit, Miss) * Electrode (2: Fz, Cz) was conducted. There was a significant interaction for Time * Performance * Electrode, [$F_{(4, 76)} = 2.801$, $p = 0.032$, $\eta^2 = 0.006$] and this is illustrated in Figure 33. All other main effects and interactions were not significant (Time [$F_{(2.655, 50.449)} = 1.385$, $p = 0.259$, $\eta^2 = 0.024$], Performance [$F_{(1, 19)} = 0.157$, $p = 0.697$, $\eta^2 = 0.002$], Performance * Electrode [$F_{(1,19)} = 0.326$, $p = 0.573$, $\eta^2 = 0.001$] and

Performance * Time [$F_{(4, 76)} = 0.444$, $p = 0.777$, $\eta^2 = 0.004$]).

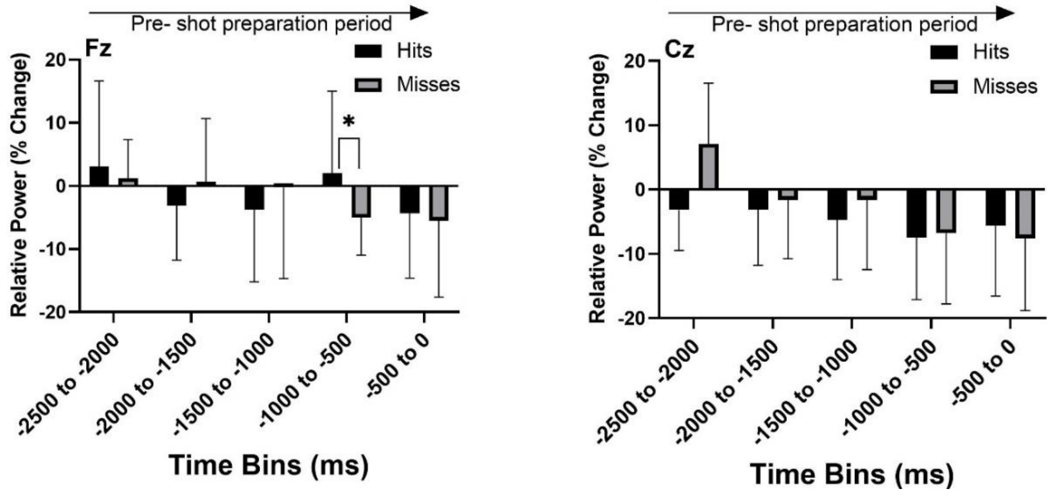


Figure 33. Relative power change (%) from baseline for successful and unsuccessful putts at the Fz and Cz across the pre-shot preparation period (p < 0.05).*

Paired sample *t*-tests were performed to examine the significant interaction and after the Bonferroni correction, there is a significant difference between power at hits (M = 2.024 % change ± 17.84) in comparison to misses (M = -5.039 % change ± 7.68) at the time period -1000ms to -500ms, [$t(1) = 1.218$, adjusted p *value* = 0.05] at the Fz electrode (Figure 34). No other time windows are significant. Although, visual inspection of the time frequency plots on an individual basis found not every participant showed this same pattern with seven participants exhibiting the opposite pattern (*i.e.* a greater decrease in theta for the hits in comparison to misses).

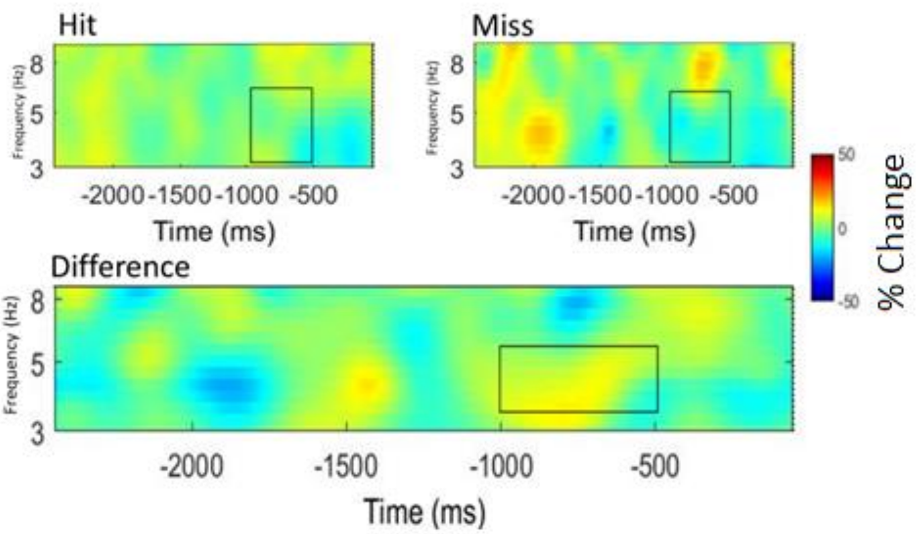


Figure 34. Time Frequency plot showing the differences in hits - miss in relative power at the electrode Fz over the pre-shot period -2500 to 0ms . As indicated by the black

squares on the frequency plot and shown in the bar chart above there is a significant difference in power at the time window -1000 to -500ms.

SMR Oscillation

To explore if there is a difference in power based on hits and misses in the SMR (13-15 Hz) region, throughout the pre-shot period (-2500 to 0ms), firstly, scalp topography maps were produced to visually inspect the data to be able to target electrodes for statistical testing (Figure 35). As illustrated in the scalp map, for successful shots there is a decrease in SMR activity, across the scalp but this is maximal at sensorimotor cortex. In contrast there is an increase in SMR activity for unsuccessful performance in the sensorimotor cortex.

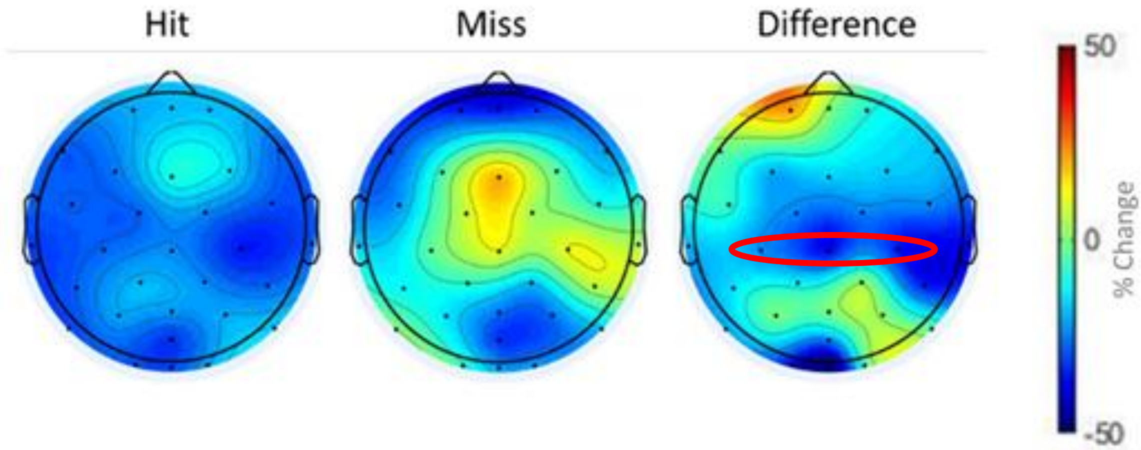


Figure 35. Scalp topographic maps representing SMR (13-15Hz) activity for successful and unsuccessful performances across the pre shot period -2500ms to 0ms after baseline correction. The scaling represents the relative change in power (%) from baseline with the blue colour indicating a decrease in the sensorimotor cortex. The middle dashed line circle indicates central electrodes (from left to right C3, Cz, C4).

A within repeated measures ANOVA at the SMR frequency band 13-15HZ for the Central Region with factors of Time (2: -2000ms to -1000ms, -1000ms to 0ms) * Performance (2: Hit/Miss) was conducted. These specific time bins and electrodes were chosen to allow for comparison to previous research exploring the impact of SMR on golf putting performance (Cheng et al., 2015). There was a significant interaction for Time * Performance [$F_{(1, 19)} = 9.008$, $p = 0.007$, $\eta^2 = 0.025$] and this is illustrated in Figure 36. The main effects for time [$F_{(1, 19)} = 0.115$, $p = 0.738$, $\eta^2 = 0.002$] and performance [$F_{(1, 19)} = 1.213$, $p = 0.285$, $\eta^2 = 0.037$] were not significant. Post hoc paired *t*-test comparisons did not reach significance after Bonferroni correction: -2000 to -1000ms time window, [*t*(38) = 1.188, adjusted *p* value = 0.425 and -1000 to 0ms time window [t(38) = 0.109, adjusted *p* value = 0.913].

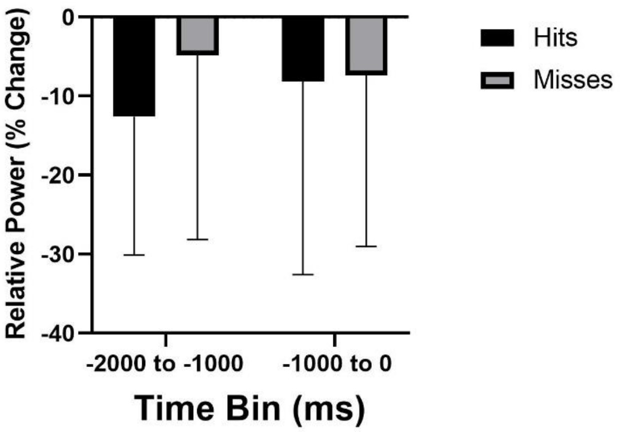


Figure 36. Change in relative power (%) from baseline during the pre-shot preparation period for SMR activity (13-15Hz) at the central region.

Beta Oscillation

As seen in Figure 37, the scalp topography maps highlighted there was a decrease in power in the sensorimotor region for successful shot in comparison to unsuccessful shots. Successful shots are associated with a large decrease in beta over right central electrodes, unsuccessful shots are associated with an increase in beta over central electrodes.

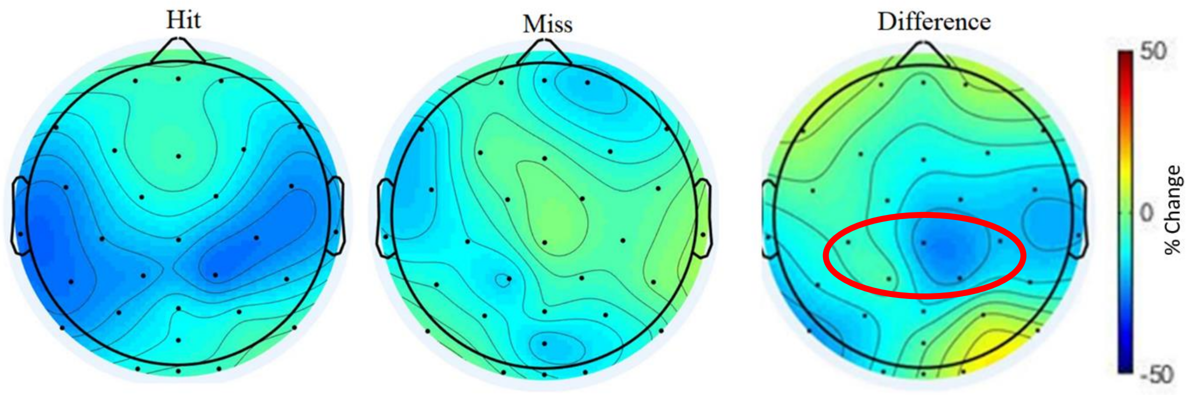


Figure 37. Scalp topographic map showing the difference in power (percentage change) for hits- misses across the whole epoch after baseline correction for all electrodes. The blue colour represents a decrease in power for hits in comparison to miss located in the in the sensory motor region. The yellow/green colour represents limited differences in power for hits in comparison to misses. The middle circle indicates central electrodes (from left to right C3 top row, CP1 bottom row, Cz top row, CP2 bottom row, C4 top row).

To explore if beta power changes over the epoch, a repeated measures ANOVA was completed using the electrodes identified in the visual inspection of the scalp maps, Performance (2: Hit, Miss) * Time (2: -2000 to -1000ms/ 1000-0ms) for the central-parietal region (C3, Cz, C4, CP1 and CP2). There was a significant interaction for Performance * Time [$F_{(1,19)} = 7.133$, $p = 0.015$, $\eta^2 = 0.024$]. There was however, no main effects for Performance [$F_{(1,19)} = 1.832$, $p = 0.192$, $\eta^2 = 0.058$] or Time [$F_{(1,19)} = 0.070$, $p = 0.794$, $\eta^2 < 0.001$].

To explore the Performance * Time interaction in more detail scalp topographies for each time window were created (see Figure 38). In relation to the Performance * Time interaction, there appears to be earlier suppression of beta power for the hits at -2000ms to - 1000ms in comparison to the misses, whereby the suppression does not start until -1000 to -500 (Figure 39, also visible in time frequency plot in Figure 26). There is a decrease in power as a function of performance at the time window -2000 to -1000ms [$t_{(18)} = 2.282$, p = 0.03]. There is no difference at the -1000ms to 0ms time window (see Figure 38). However, visual inspection of the time frequency plots on an individual level revealed not every participant experienced a greater decrease at -2000ms to -1000ms with three participants experiencing an increase in beta power relative to baseline.

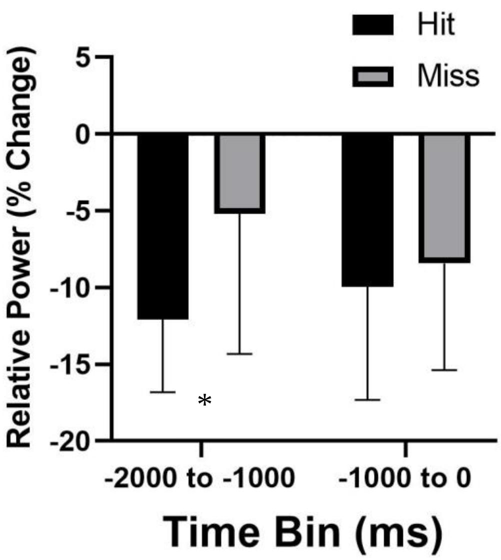


*Figure 38. Change in relative power (%) from baseline during the pre-shot preparation period for beta activity (13-30 Hz) at the central region , with a greater decrease for successful putts in comparison to unsuccessful shots, especially at -2000 to -1000ms time window (95% CI, * p = 0.03).*

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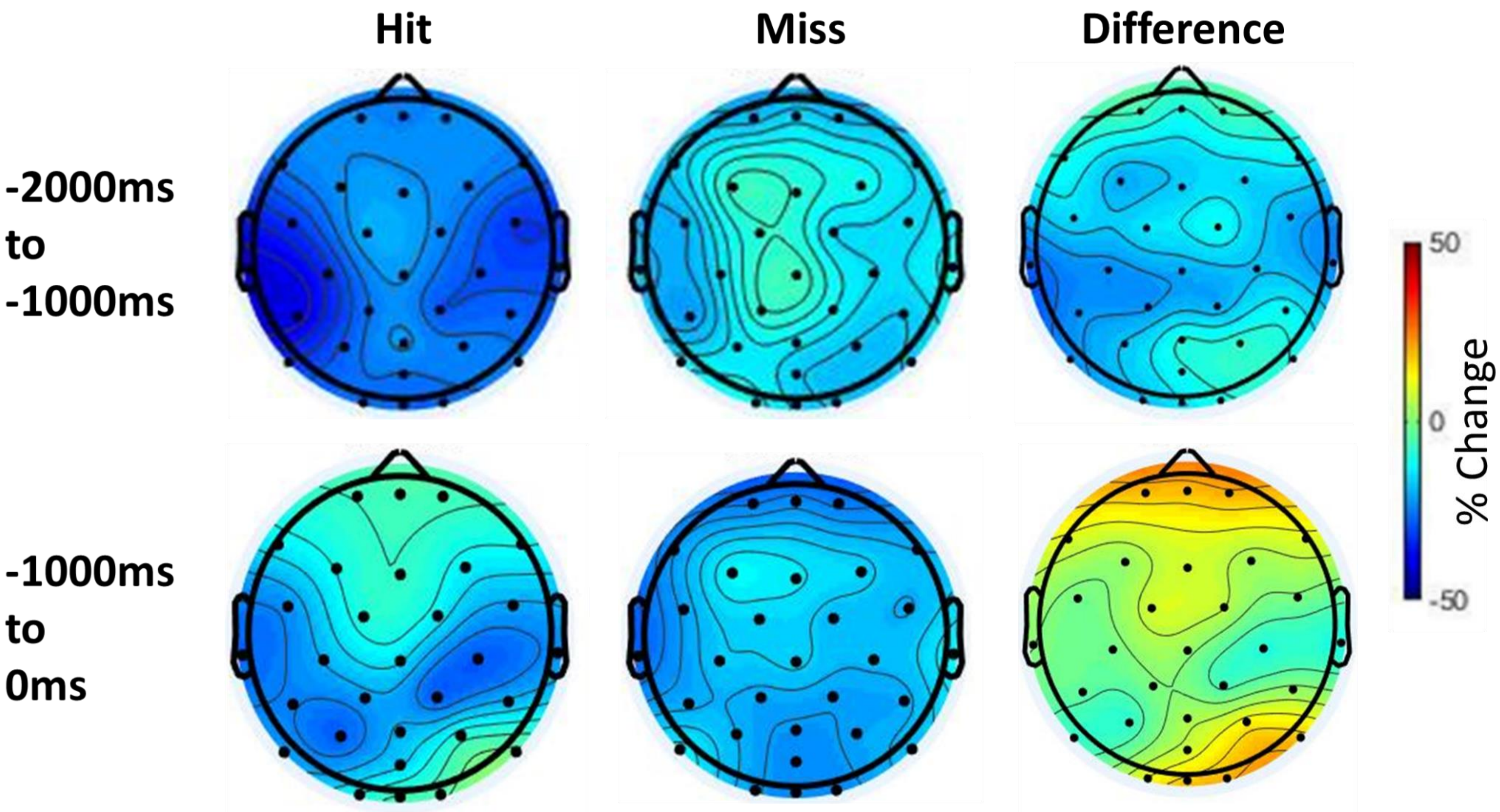

Figure 39. Scalp map representing beta (13-30 Hz) activity over the two selected time windows (2000-1000ms and 1000-0ms). There was a difference in relative power at the -2000ms to -1000ms time period with a greater decrease in power for successful shots in comparison to unsuccessful shots in the central region.

MRCPs

There was a significant difference in mean activity between hits and misses ($t_{(29)}$ = 2.178, p = 0.03 r^2 =0.14) for the whole epoch. As shown in Figure 40, there was an observable BP at the electrode Cz for successful putts but not misses. The scalp topographic map for the unsuccessful putts indicates eye movements and this may be masking the BP, but nevertheless as seen in the ERP waveform (Figure 40) there is not a clear BP. To explore the BP in more detail, visual inspection was used to find peak ±100ms (-750 to -550ms). The mean amplitude of the interval (-750 to -550ms) was considered for statistical analysis using the Analyzer statistical tool. When exploring the BP, statistical testing revealed a differences in activity as a function of performance during the interval [$t_{(19)}$ = -1.008, p = 0.05].

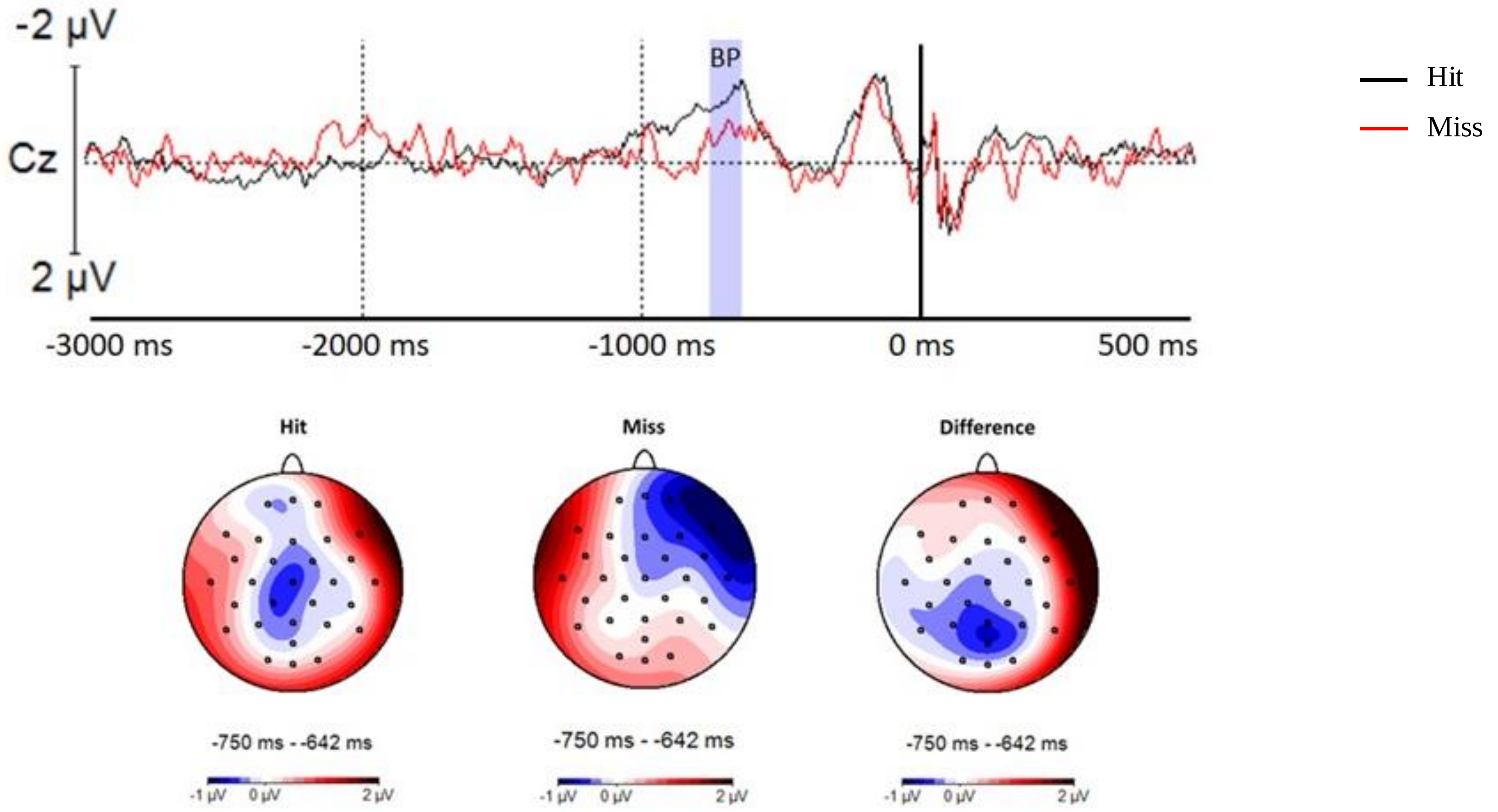

Figure 40. ERP waveform and scalp topographies for successful (hit) and unsuccessful (miss) putts at the electrode Cz. The BP is more visible in successful putts (black line) in comparison to unsuccessful putts (red line). There is no clear BP for unsuccessful puts. Topographical scalp distribution shows the BP is maximal over midline central area for successful shots, whereas for unsuccessful shots there is eye movements. The choice of trigger has limitations as the motor action (initiation of the putter) can be seen within the ERP waveform with 0ms representing contact between the putter and ball. Red colour represents an increase and blue colour represents a decrease.

To explore the eye movements further we looked at the electrodes FP1, FPz and FP2. As seen in the ERP waveforms (see Figure 41) despite data processing (ICAs and artifact rejection) there are eye movements specifically related to the golf putting action. Typically, in golf putting the golfer saccades out to the hole several times, before initiating the putting action and these saccades are visible in the ERP waveform (Figure 41). Paired *t*-test, however, revealed significant differences in mean activity as a function of performance with successful putts having significantly less mean activity in comparison to unsuccessful putts at FP1 [$t_{(29)} = 2.3$, $p = 0.02$], FPz [$t_{(29)} = 2.04$ $p = 0.04$] and FP2 [$t_{(29)} = 2.53$, $p = 0.01$]. Thus suggesting golfers move their head and eyes less in successful putts in comparison to unsuccessful putts. This movement artifact has not previously been reported within the literature findings, and, as a result these findings would need to be treated with caution. The eye movement may limit the feasibility of collecting golf putting data using a representative task design. Improvements in the quality of data may increase through using horizontal and vertical electrooculograms (EOG) placed at external canthi (HEOG) and below and above the left eye (VEOG) as these were missing from this study

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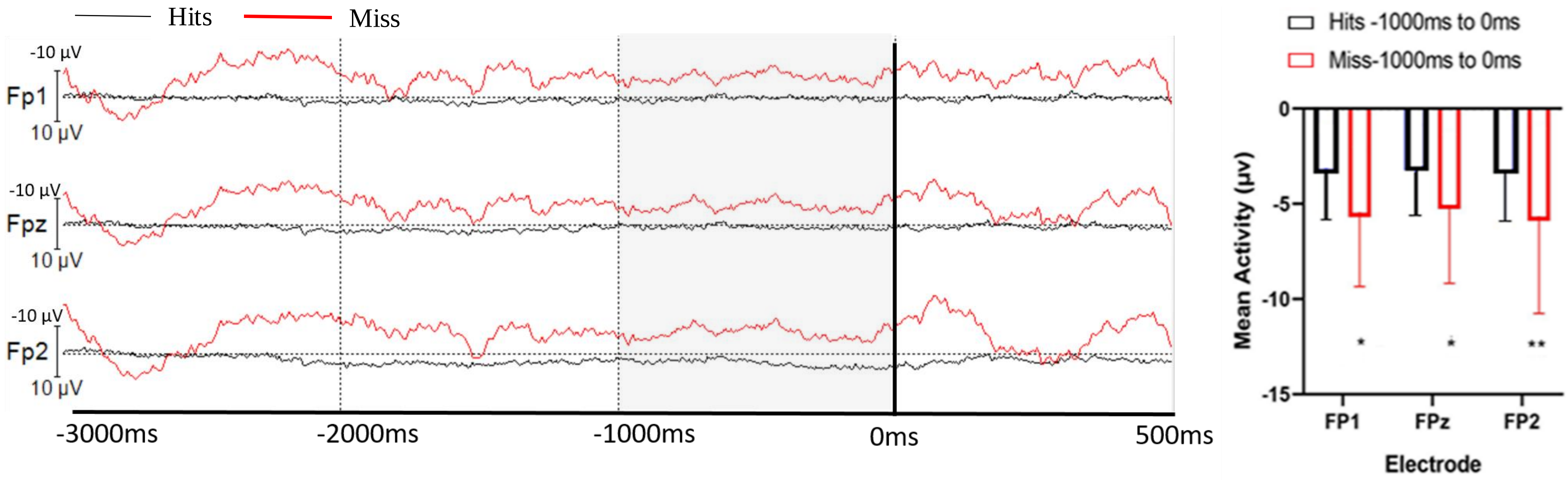

Figure 41. Differences in movement related cortical potential in frontal electrodes between hits and misses throughout the whole epoch mean activity (95% CI) during the final second (p = 0.05, ** p = 0.01). The black line represents hits and the red line represents miss putts. The grey section relates to -1000ms to 0ms time period and the data shown in the bar chart.*

5.4 Discussion

The two main aims centered around, firstly, to explore if the QE intervention led to any differences in neural activity and secondly, to explore expertise-based differences in the EEG data by comparing successful vs. unsuccessful putts. The first aim could not be realised in this study. The combined approach of collecting EEG and eye tracking data was feasible and clean data could be collected which does offer promise for future research. Although, the main problem resulted from a lack of trial numbers when using the four conditions of QE hit/miss and Control hit/miss, therefore when using a combined approach increasing trial numbers needs to be considered. Increasing trial numbers does bring about its own conceptual challenge as adding more trials does decrease the representative nature of the task design (Brunswik, 1956) and arguably the ability to disseminate the findings into the applied domain (Roca & Williams, 2016). To address this problem future research should conduct longitudinal research to examine brain activity and gaze behaviour over multiple sessions. In relation to our second aim, our results indicate that there are indeed performance-related changes in cortical activation during motor programming and these will be considered in the remaining part of this discussion.

5.4.1 Frequency bands

Our findings did reveal there were observable differences in neural activity within the frequency bands –theta, alpha, SMR, beta and these will be discussed in the section below. We will start with alpha due to the dominance of studies in the sporting literature exploring alpha and its link to performance (Park et al., 2015).

A relative increase in alpha power (from baseline) was found for successful putts at the time window (-1000ms to -500ms) in comparison to missed putts (which showed a relative decrease from baseline in alpha power at this time window) in the right central area (C4). Research has found a period of increased alpha power is indicative of active inhibition (Hummel et al., 2002; Klimesch et al., 2007). The C4 electrode is associated with arm and hand region of the right primary sensorimotor area and is reflective of fine motor control (Babiloni et al., 2008; Cheron et al., 2016). More specifically a relative increase in alpha power at C4 for successful shots is suggestive of inhibition of left arm (Klimesch et al., 2007). Furthermore, these findings are in support of inhibition hypothesis characterised by alpha activity as neural signature of inhibitory top-down control, (Klimesch et al., 2007). The inhibition hypothesis is task specific were synchronized alpha activity can be observed selectively i) in tasks where a learnt response must be withheld and ii) over brain areas that are not task relevant (Klimesch et al., 2007). Given our findings whereby maximum relative increase alpha power was at C4, it could be concluded inhibition is reflective of withholding a learnt motor response. These findings have implications for golf putting and coaches, suggesting that a cortical control of the left arm and hand movements (inhibition) is linked to successful performance. In particular as all golfers in this study were right-handed meaning the left hand is responsible for determining the direction of the putter face and keeping the putter square at contact (Pelz, 2000). Our findings suggest successful shots were related to superior fine motor control underpinned by inhibition of the left arm/hand and this merits an exciting area for future research.

However, it must be noted that our findings are also not consistent with other research using EEG in golf putting (Babiloni, et al., 2008; Cooke et al., 2014; Gallicchio et al., 2017) or the neural efficiency hypothesis (Del Percio et al., 2009). Babiloni et al. (2008) found when comparing differences between successful and unsuccessful putts within elite golfers, successful putts were preceded by a greater reduction in alpha power (10–12 Hz) in the premotor and motor cortex (e.g., Fz, Cz, C4). Moreover, in contrast to our findings, Babiloni et al. (2008) found for successful putts the desynchronisation in relative alpha power was maximum over the right primary sensorimotor cortex (C4). Babiloni et al. (2008) findings are consistent with the evidence that for voluntary bimanual tasks self-paced movements are preceded by event-related desynchronization (e.g., Leocani et al., 1997; Pfurtscheller & Aranibar, 1979; Pfurtscheller & Lopes da Silva, 1999). However, there are differences in the methodologies used in our study and in Babiloni’s study which makes comparisons difficult. For example, Babiloni et al. (2008) participants used a variety of hole diameters, including the standard size 108 mm and two holes of smaller diameters (80 mm or 60 mm) depending on success rate in preliminary testing and had a different baseline (5-4 seconds).

Cooke et al. (2004) also found a decrease in alpha power in the central regions. More specifically, Cooke et al. (2004) found a pattern whereby there was an initial increase followed by a sudden drop in the last second preceding movement initiation. This pattern was stronger for experts in comparison to novices. These findings are supported by Gallicchio, et al. (2017) who found alpha power was lowest over the central regions. It is believed a decreased in alpha power in the central region is reflective of a decrease in movement-specific conscious processing and a marker of psychomotor efficiency (in line with the neural efficiency hypothesis). As motor expertise increases task relevant thoughts decrease consistent with increased in automaticity related to greater skill development (Fitts & Posner, 1967). However, the multi-action plan (MAP) model (Bortoli et al., 2012) suggest optimal performance in experts can be characteristed in two main ways: Type 1 (fluent, automatic, and procedural) autonomous processing and Type 2 (competent, regulated, and declarative) controlled processing, developed through a large amount of deliberate practice (Ericsson, 2007). Type 1 performance is consistent with the neural efficiency whereby you would see a decrease in alpha reflective of autonomous skills and goal-relevant attentional focus when approaching shot release (Doppelmayr et al., 2008). Consistent with the wider literature suggesting when attention is directed to external stimuli (as recommended for optimal attention in highly skilled golfers, Wulf, 2007) a decrease in alpha power over sensorimotor areas has been found (Hanslmayr et al., 2005). Type 2 performance, 'optimal-controlled performance' requires effortful processing, suggesting our findings are indicative of efficient proficiency not necessarily efficiency in effort (Bertollo et al., 2016). Furthermore, the neural efficiency hypothesis has been supported by studies using the expert–novice paradigm, and it predicts experts have a decrease in cortical activity compared to novices, particularly measured through alpha activity (Cooke, 2014, Hatfield et al., 2004). Our study is one of the few studies that have explored expertise as a function of performance in highly skilled golfers rather than exploring the neural efficiency hypothesis using the expert–novice paradigm. Taken together, these findings highlight how relationships between baseline alpha power and subsequent cognitive–motor processes are quite complex. Future research into the directional relationship between alpha power at C4 and performance is required to progress knowledge underpinning expert performance, with a particular focus on the concepts of inhibition and neural efficiency (Park et al., 2015).

Evidence has suggested that in addition to alpha, action inhibition involves several brain regions working together with the motor cortex, including the prefrontal regions (Swann et al., 2009). In support of the prefrontal region playing a role in active inhibition our findings found there was a difference in theta power for hits in comparison to misses in the time window -1000-500ms. For hits there was an increase in power at the Fz region in the frontal midline theta (Fmθ) during this time point, whereas misses had a decrease in theta power during the same time point. Increases in Fmθ are characteristic of expert performance in a range of golf/rifle shooting (Baumeister et al., 2008; Doppelmayr et al., 2008) indicative of increased attention during the aiming period in the lead up to the shot in experts in comparison to novices. Our findings suggest that for successful putts, a golfer maintains sustained attention, and this is effortful (Sauseng et al., 2007). However, in contrast to our findings, Kao et al. 2013, found lower Fmθ power was associated with the best performances, whereas a higher Fmθ power was associated with the worst performances, in skilled golfers (using a within participant design). Kao et al. (2013) speculated that higher Fmθ power in skilled golfers may be detrimental due to excessive amount of attentional engagement leading to a disruption of the automatic skill execution. Although an alternative explanation for optimal performance in skilled athletes, is that superior performance is experienced due to their ability to consciously monitoring processes relative to action components and to focus their attention on the right things at the right time (di Fronso et al., 2018). In support of this, it is believed an increase in Fmθ is associated with attention regulation, i.e., helping individuals adapt their motor behaviour to achieve improved performance (Cavanagh et al., 2009; Cohen, 2011) and with task monitoring and error detection within the motor cortex (Luu et al., 2004). Therefore, it could be proposed when participants are successful, they are more able to focus their attention on relevant internal and external components and adapt their behavioural response in line with the task demands.

Our findings reflect a greater decrease in Sensorimotor Rhythm (SMR: neural oscillations between 13-15 Hz) activity related to time for successful putts in comparison to unsuccessful putts in the central region. SMR is thought to reflect the preparation, execution, and imagery associated with a motor act. A decrease in SMR in sensorimotor area is reflective of movement planning or movement execution (Pfurtscheller et al., 2006) and reflects cortical activation (Klimesch et al., 2007), suggesting successful performance is underpinned by enhanced preparation. Previous studies exploring performance in golf putting have also found differences in SMR and beta activity (neural oscillations between 13-30 Hz) related to the motor cortex as a function of performance (Chang et al., 2011). Similarly, to the observed SMR suppression, we found a decrease in beta power for hits in comparison to misses in the central-parietal region over the motor cortex (C3, Cz, C4, CP1, CP2) at the time point -2000ms to -1000ms. A decrease in beta power is thought to reflect the activation of the sensorimotor networks (Pfurtscheller & Lopes da Silva, 1999) in both the planning and processing (including sensory and cognitive aspects) as well as the movement of the action (Pfurtscheller, et al., 2003). In support of our findings Cooke et al. (2014) found expertise (experts in comparison to novice) in golf putting was linked to a greater decrease in beta power in the final two seconds preceding execution of the golf putt. However, Cooke et al. (2014) did not state the trigger method so it is not clear if 0ms represents the time of movement initiation or contact therefore, there could be differences in triggers used between our study and Cooke et al., 2014, making it difficult to compare relative timing effects. Furthermore, in support of our findings, Del Percio et al. (2009) reported experts have a greater decrease of beta amplitude during the aiming period in comparison to novices when shooing. Del Percio et al. (2009) interpreted the greater decrease in beta amplitude to mean experts experience successful visuo-motor performance as they engage in enhanced preparation. Taken together with the decrease in SMR at the time window -2000 to -1000ms for successful putts the findings would suggest that optimal performance was indicative of enhanced preparation that started earlier in comparison to the unsuccessful putts. These findings are encouraging with observable differences in neural activity as a function of performance across the frequency bands allowing us to conclude consistent with Cooke et al. (2014) that successful performances are associated with enhanced programming of the movement (e.g. force and direction parameters) during the final 2 s preceding movement.

5.4.2 Movement Related Cortical Potentials (MRCPs)

Successful putts were associated with greater preparation reflected in the onset of BP (and greater BP peak negativity) whereas there was not an observable BP for unsuccessful putts (potentially due to eye movements). The BP reflects activation of subcortical and cortical generators necessary for motor preparation (Rektor 2003). A greater BP peak negativity is believed to characterise greater movement preparation (Mann et al., 2011). The lack of BP and increase in eye movements for the unsuccessful putts is interesting particularly as the BP is speculated to play a role in the detection and pairing of task-relevant environmental features required in the response execution (Brunia & van Boxtel 2000). This therefore suggests differences in decision making and perceptual-cognitive processes between the successful and unsuccessful putts. The finding of enhanced motor readiness is linked to expertise, is consistent with Mann et al. (2011) who found greater BP negativity (particularly in central recording locations) for the expert golfers compared with non-experts. It must be acknowledged there were limitations within the EEG analysis, as saccades could be detected in the MRCPs despite correcting for blinks. Interestingly, there was a reduction in saccades for hits in comparison to misses prior to shot execution. Critically for successful putts (hits) a clear BP could be seen but for unsuccessful putts eye movements were present suggesting that the golfers were moving their eyes prior to initiating the action. For successful putts, the reduction in head movement in the final seconds prior to the shot could be indicative of more efficient processing and clarity of decision, whereas the extra saccades i.e., looks to the hole, could be representative of indecision or lack of confidence in the putt the golfer is about to hit. Furthermore, due to the limits of the choice of trigger and the use of 32 channel EEG system that did not include horizontal and vertical electrodes, further study is required before any conclusions can be drawn.

Our findings highlight that preparation for a voluntary movement consists of both BP and the pre-movement desynchronisation of beta/SMR. Taken together, the findings support the notion that superior behavioral performance is related to an increase in advanced motor preparation (Hung et al., 2004, Del Percio et al., 2009, Di Russo et al., 2005). Based on the neural efficiency hypothesis (Del Percio et al., 2009) it would also be expected to see desynchronisation of alpha (Pfurtscheller, 2014), rather than increase in alpha. However, it could be argued our alpha findings are indicative of proficiency (i.e. an individual’s ability switch effectively between an automated and a more controlled execution according to the task and situational demands) using their years of deliberate practice to regulate their actions (Bertollo et al., 2016). Therefore, we propose future study to continue to explore neural activity in relation to performance within highly skilled athletes.

5.4.4 Strengths and limitations

This study reinforces neural activity can be used to differentiate between successful and unsuccessful performance. There are, however, limitations within the methodological design, including; a) the head/eye movements found in golf putting, b) trigger choice (i.e., deciding to use contact and not initiation of the movement) and c) lack of horizontal and vertical eye electrodes did impact on the data quality. In particular, further research is required to assess feasibility of conducting MRCPs research using representative task designs for golf putting. In the future it is hoped technology advancements will allow the collection of synchronised eye tracking and EEG data capture and this will potentially allow the EEG data to be timestamped by the gaze behaviour, either through fixations (Baccino & Manunta, 2005). To our knowledge, no studies have reported successful synchronisation but the potential of this research and the feasibility, including outlining current challenges with this approach are discussed in detail in Ladouce *et al.* (2017). Moving forwards the choice of trial numbers is essential when comparing performance and QE durations and we recommend longitudinal research over multiple sessions.

5.5 Conclusion

A difference in neural activity for hits was observed with successful shots associated with earlier and enhanced preparation, in comparison to misses. However, from an applied perspective, further work is required to understand variation in individual difference. Our findings suggest any interventions delivered to athletes which incorporate manipulating neural activity need to individually profile each athlete because it cannot be assumed all individuals are going to respond the same. The ability to tailor findings to individuals is critical, particularly when relating findings back to elite athletes, as group average does not apply (Baker & Farrow, 2015). These findings also have important implications for the eye tracking interventions delivered on a group level, as there are differences in the way individuals prepare pre-shot in the brain therefore it would be expected to see differences in the gaze strategies used.

Chapter 6: Study 2c - Exploring the impact of a QE intervention on golf putting performance over multiple sessions.

The current chapter details the rationale for, and results of Study 2b. Study 2b, seeks to expand on Study 2a (outlined in Chapter 4) and address the main design limitation of Study 2a to establish if the QE performance benefit can be replicated or whether the results were due to a confound in the design. In Study 2a, the participants completed 70 control putts, then a QE training intervention, followed by 70 QE intervention putts (same surface and position as the control putts just a different order). In Study 2a, participants were unable to start with the QE training intervention as they were unable to unlearn the QE intervention within the same session. This distinction was previously unknown, as to our knowledge no other study had reported completing a within participant QE intervention design before. The implications of the design meant, the QE intervention putts did not start at putt 1, but rather putt 71 in terms of practice on the surface. This is problematic as the analysis of the data across the testing session in Study 2a revealed, the overall benefit of QE most likely reflected a practice effect. Therefore, this study was designed to address the limitations of the design and to test participants using a counter-balanced design, whereby participants attended two days of testing, one week apart to explore the impact of QE duration on performance.

6.1 Introduction

In Study 2a (outlined in Chapter 4), following the QE intervention training, participants did experience an increase in mean performance in comparison to the control condition, in line with our expectations based on previous research (Vickers, 2007). Although, it was unclear how practice impacted on the success of the training not only due to the aforementioned practice effects across the whole testing session, but due to the fact the QE effect seemed to be restricted to the first block of trials. For example, in the control condition, (pre QE intervention training) there was a significant decline in performance in the 1st block (i.e., the first ten putts of the session) in comparison to putts taken in later blocks in the testing session. Performance was also significantly related to putt block for the control condition, with an increase in performance as the participants completed more putts. Performance was not related to putt block in the QE intervention condition, meaning the same practice effects were not present in the QE intervention putts, as the participants did not experience a decline in performance during the first block, possibly due to the practice effects carrying over from the control condition. Understanding how QE duration impacts on performance, especially in the first block when the putt is unfamiliar is critical, therefore the study needed to be designed in a way where the practice did not interfere with the design. Therefore, this study has been designed where testing is a week apart so the impact of the QE training on the 1st ten putts of the testing session (i.e., unfamiliar) can also be explored.

Currently there is limited research on identifying the function of the QE duration (Campbell *et al.* 2019) and in Study 2a the QE intervention changed other visual measures, final viewing time on the ball prior to QE. Additionally, we have not found that longer QE duration is linked to performance. Although these findings go against the norm of the evidence base (Lebeau et al., 2016), there are two other studies that reveal findings consistent with our findings in golf putting (Campbell *et al*. 2019; van Lier *et al.* 2010). In Study 2a when considering QE duration and performance on a trial by trial basis, considerable within and between variation was reported. There were also some unanswered questions based on the optimal duration of QE as a QE duration of <2000ms still led to participants being able to successfully putt the ball; a QE duration of 2-3 seconds did not always lead to increased success and the same QE duration could lead to both a successful and unsuccessful putt. These findings cannot be explained via current QE theory (Moore et al., 2012; Vickers, 2007; Vine et al., 2011), however, they were consistent with what we found when measuring QE duration in a representative task design with highly skilled golfers in Study 1 (Chapter 3). From an applied perspective, Farrow and Panchuk (2016) have called for QE researchers to consider when thinking about elite athletes:

> "*Whether the idiosyncrasies observed in their QE behavior (which fall outside of what is deemed prototypical) actually underpin their phenomenal capabilities. In these cases, would it not be detrimental to prescribe training in accordance with the prototype? Or is it still desirable to train the athlete to the norms of the group?"*(p. 2)

The rationale for this study is therefore to complete a follow up study from Study 2a (Chapter 4) to explore the merits of QE intervention training when practice effects are accounted for. Taken together with the findings from the other studies in this thesis we aim to establish if promoting a longer QE duration is effective for performance with highly skilled golfers. Furthermore, we were interested to see how the multiple session set up, can be used to help understand the intra-individual variation we have found so far in the thesis. The main research questions for this study are:

1) Does a QE intervention designed to train optimal QE duration (2-3 seconds) improve performance once accounting for practice in highly skilled golfers?
2) Do other gaze measures such as viewing time on ball prior to QE duration change as a result of a QE intervention and what impact does this have on performance

It is hypothesised that a QE intervention will increase QE duration and associated gaze measures. At this stage, based on our findings from Study 1 (Chapter 3) and Study 2a (Chapter 4) we are predicting that a QE intervention will not improve performance even when accounting for practice.

6.2 Methods

6.2.1 Participants

Fifteen participants (11 male and 4 female), all right handed, right eye dominant and with normal or corrected vision. Mean age was 33.5 years ± 16.4 and average handicap was -2.7 ± 9.4. Mean years played golf was 25.8 years ± 15.69, average weekly practice was 15.5 hours ± 11.5, average putts per round was 32.5 ± 4.24, average green in regulation was 50.2% ± 11.1.

6.2.2 Procedure

As per Study 2a, ethical approval was granted by the General University Ethics Panel (GUEP) at the University of Stirling and consent was gained prior to testing. Participants attended testing sessions individually when an ASL mobile eye tracker was fitted to the participant by the lead researcher, used own putter and were provided with golf balls (consistent with Study 2a).

Participants completed two days of testing, one week apart (Figure 43). Participants were either taught QE instructions prior to starting to putt on Day 1 or Day 2 dependant on the counterbalanced order (Figure 42). The rest of the testing session format was the same as Study 2a.

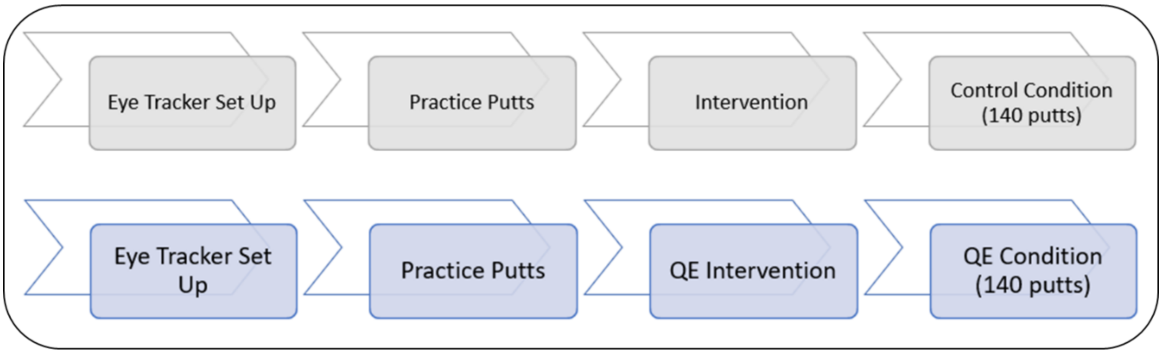

Figure 42. Schematic of Study 2b methodology.

6.2.3 Measures

The same measures were used as in Study 2a, with the exception of the additional measures of SAM PuttLab tendency, timing, consistency and overall rating (Marquardt, 2017). These ratings have been designed to allow for comparison across golfers and are comprised from different markers of stroke kinematics. The information below is a snapshot from page 36 of the SAM PuttLab 5 manual. Tendency is a measure of technique which includes face at address, face at impact, path direction, face on path, impact spot and rotation at impact. Timing includes time to impact, backswing timing, impact timing, path symmetry. Consistency includes consistencies of face at address, face at impact, path direction, path length, face on path, impact spot, rotation at impact, backswing time, impact time, impact velocity. Lastly, overall rating encapsulates technique (25%), timing (25%) and consistency (50%). Detailed information on each marker is provided in the SAM PuttLab manual and Marquardt (2017) paper explaining the concept of SAM PuttLab.

6.2.4 Statistical Analysis

In all analyses significance was accepted at $p < 0.05$. To establish whether QE intervention was effective, initial analysis explored whether gaze variables changed pre- and post-intervention. A repeated measures ANOVA was conducted to compare the differences in QE duration (% trials) between the control and QE condition and within the bins (7: 500-1000ms, 1000-1500ms, 1500-2000ms, 2000-2500ms. 2500- 3000ms, 3000-3500ms, >3500ms). A series of paired *t*-tests were used to compare the significant gaze measures from Study 2a, namely, viewing time on the ball prior to QE (in seconds) and average fixation.

To explore any potential variation in the data, a series of statistical tests were used. The first test was a paired *t*-test to examine mean change in performance. The second analysis conducted was repeated measures ANOVA; Condition (4) * Putt Block (putt block; 0-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-70). Putt block (consistent with Study 2a), putt block is defined as the putt intervals whereby a block consists of 10 putts so there is a total of 7 blocks for each condition with Block 1 representing the first ten putts in the condition and Block 7, representing putts 60-70 i.e., the end of the putts in that condition). Conditions are Control 1 (70 putts); Control 2 (70 putts) and QE 1 (70 putts); QE 2 (70 putts). Please note all control putts were taken on one day and all QE putts were taken on another day of testing. A multivariate linear regression will be conducted to see which condition (control or QE) can best predict performance using the four conditions (Control 1 (70 putts); Control 2 (70 putts) and QE 1 (70 putts) QE 2 (70 putts) and performance by putt block (a putt block is defined as the putt intervals whereby a block consists of 10 putts so there is a total of 7 blocks for each condition with Block 1 representing the first ten putts in the condition and Block 7, representing putts 60-70 i.e., the end of the putts in that condition). A further multivariate linear regression will be conducted to explore differences in performance and practice rates between this present study and Study 2a.

A repeated measures ANOVA was conducted to explore any differences in the relative success at Condition (2; control vs QE) * QE duration (7 time bin). Bins were as followed; QE duration (100-500ms followed by 500ms bins until 3500+ms).

A series of paired *t*-tests were also conducted to see if there was a change in kinematic variables between Day 1 and Day 2 of testing. Variables were tendency, timing, consistency and overall rating.

6.3 Results

6.3.1 Visual strategies Pre and Post Intervention

To explore if the QE intervention was successfully applied a repeated measures ANOVA with factors of condition (2) * time (7 percentage of trials in each bin). As shown in Figure 43, there was a significant interaction [$F_{(2.561,25.606)} = 15.077$, $p < 0.0001$, $n^2 = 0.312$]. There was a clear shift in profile with a positive trend for an increase of trials with longer QE duration in the QE condition in comparison to the control condition [$F_{(1,10)} = 4.053$, $p = 0.072$, $n^2 < 0.001$]. Lastly there was a significant main effect for time [$F_{(2.552,\ 25.5237)}$ = 7.193, p = 0.002, n^2 = 0.201]. To explore if there was an increase in trials in the 2-3 seconds optimal QE duration as per intervention recommendations in the QE intervention condition in comparison to control condition, a series of post hoc paired *t*- tests were completed for this time period (Table 10). Taken together, the findings highlighting the QE intervention was successful applied.

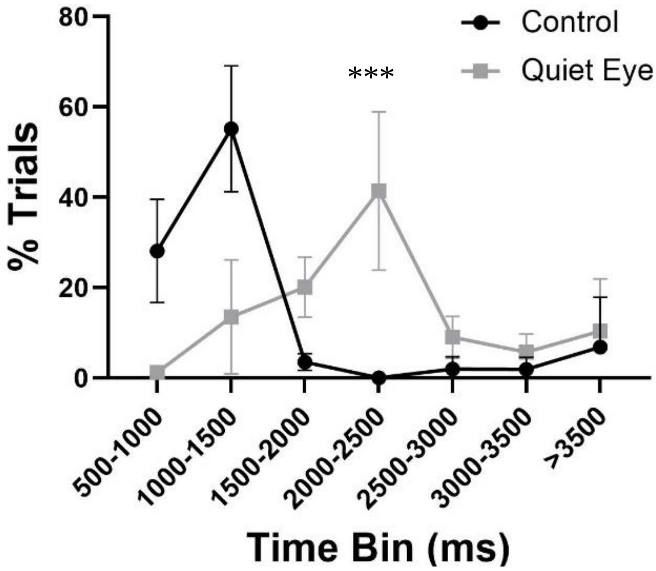

Figure 43. A clear shift in profile for the QE intervention putts in comparison to the control putts (95% CI).

Table 10. Significant increases in percentages trials in each of the trial bins associated with optimal QE duration.

Time Window	*Mean of Control*	*Mean of QE*	*Difference*	*SE of difference*	*t ratio*	*df*	*P value*
15000-200ms	3.516	20.11	-16.59	3.162	5.247	24	< 0.001
2000-2500ms	0	41.43	-41.43	7.766	5.335	24	< 0.001
2500-3000ms	1.978	9.011	-7.033	2.236	3.145	24	0.004

In contrast to Study 2a there was not a significant change in viewing time on the ball prior to QE duration between the control and QE intervention or average fixation (p > 0.5), again adding to the confusion around what gaze measures does a QE intervention change.

6.3.2 Does QE intervention improve performance?

As seen in Figure 44, mean putt holed were similar between the control condition (60.19% ± 9.62) and QE condition (63.28% ± 8.20) and statistics confirmed no differences in performance [$t_{(15)} = -0.9$, $p = 0.3$].

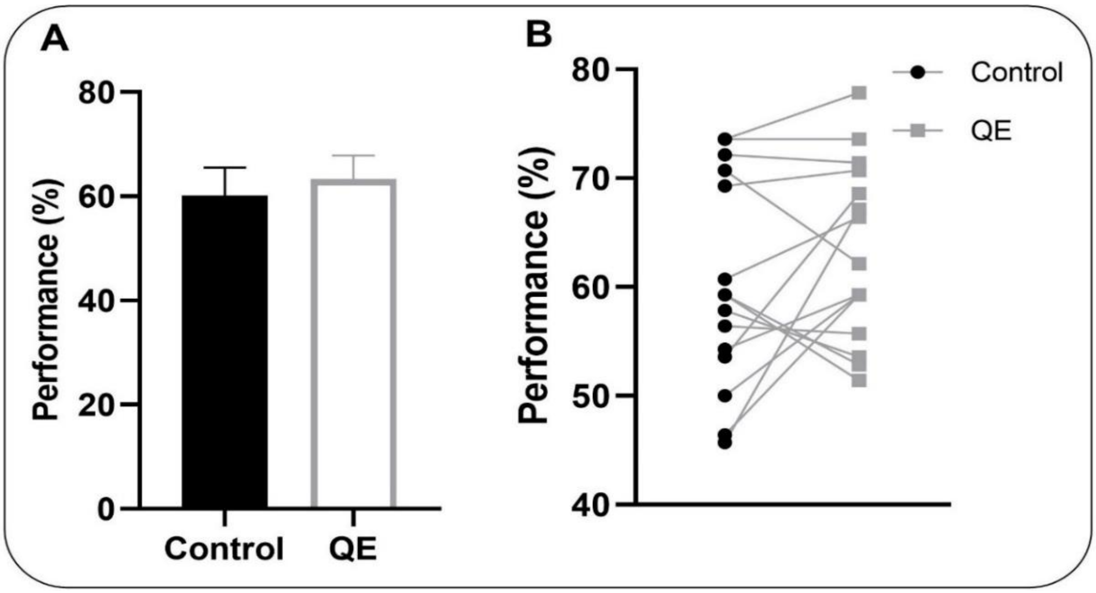

Figure 44. The impact of a QE intervention on performance. Panel A represents mean % putts holed (and 95% CI) for the control condition and QE intervention. Panel B reflects changes in individual performance, highlighting not every participant improved their performance after the QE intervention.

Closer inspection of performance data on a block level (consistent with Study 2a), as shown in Figure 45, revealed there was no interaction between putt block * condition, ($F_{(18, 420)} = 0.766$, $p = 0.740$). The main effect for putt block was significant, ($F_{(6, 420)} = 6.392$, $p < 0.0001$) highlighting differences in performance across the blocks (Figure 46). The main effect for condition was significant, $F_{(3, 420)} = 3.633$, $p = 0.01$) highlighting that performance varied across the different conditions. Post hoc testing confirmed the only block where a significant difference in performance between the conditions occurred was at Block 13 ($p < 0.05$). Unlike in Study 2a there was no difference in the first block.

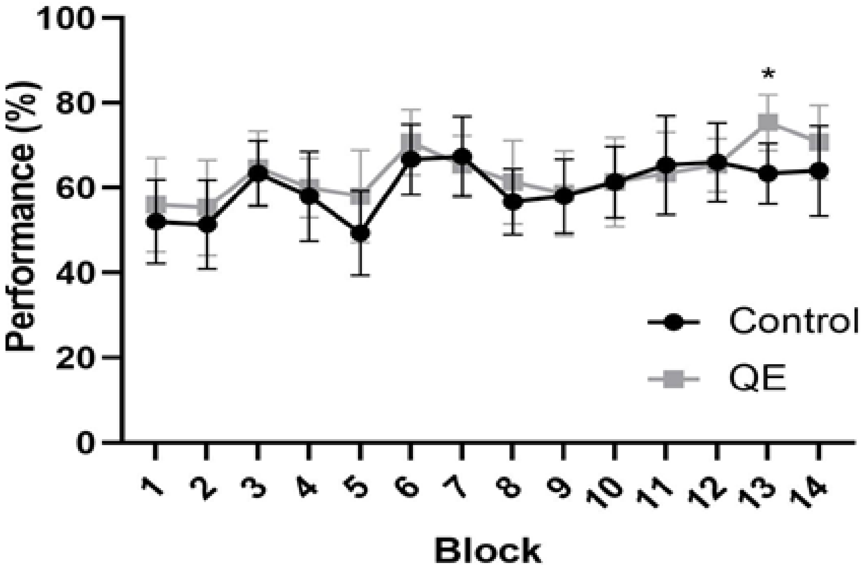

*Figure 45. Performance across the blocks in both the control and QE intervention condition (95% CI, * = p<0.005). 140 putts were taken at each testing session. There was no difference in performance based on intervention. However, in Block 13 there was a significant improvement in performance for the QE condition in comparison to the control condition (* p = 0.05).*

To expand on the analysis beyond differences, a multivariate linear regression was conducted to explore the relationship between the four conditions (control/intervention time 1 and time 2) and performance by block (Figure 46). To allow comparison to Study 2a, 70 putts will be compared for all conditions. For the all conditions vs. performance, there was a strong positive relationship between performance and block number, with the highest performance occurring at the later blocks (Control 1 r^2 = 0.6370, Control 2 r^2 =0.8003, QE 1 r^2 = 0.7101, QE 2 r^2 = 0.8548). Simple linear regression, as shown in Panel A in Figure 46 revealed there was no difference in the rate of progression across the blocks (Control 1 Y= 0.2238 * X + 4.933, Control 2. Y = 0.1333 * X + 5.676, QE 1 Y = 0.1857 * X + 5.400, QE 2 Y = 0.2333 * X + 5.581).

Comparison of performance across the two study designs (Study 2a and Study 2b) found there were no differences in performance over the 140 putts (slopes: $F_{(2, 36)}$ = 0.001, p = 0.9839). Although there was a difference in elevations suggesting performance rates and learning effects did change based on the task design and intervention condition ($F_{(2, 38)}$ = 19.56, p < 0.001).

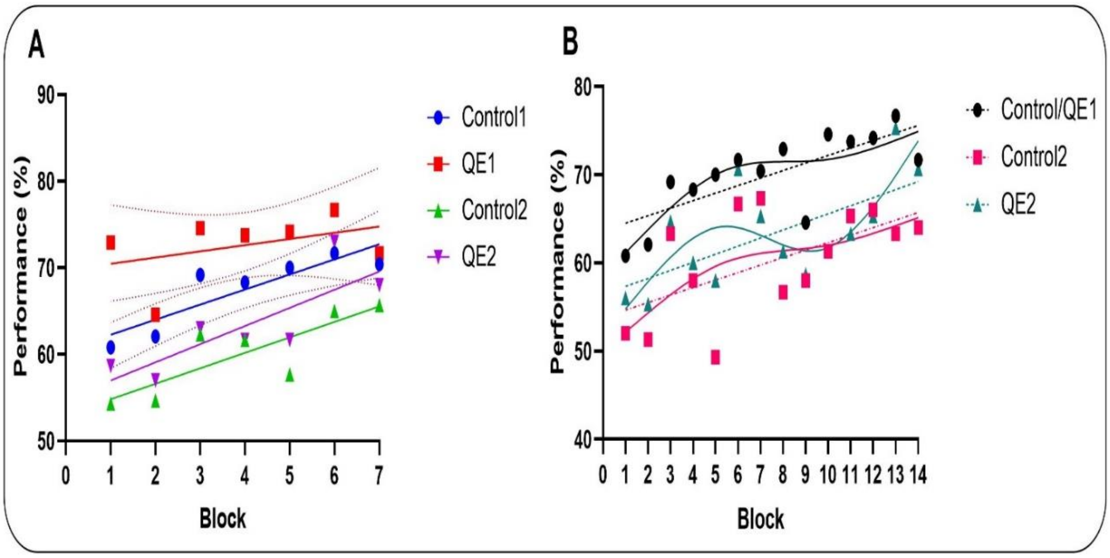

Figure 46. Linear regression showing all conditions improved through practice, but there was no difference in progression rates across all conditions (Panel A). In Panel A-1 relates to the first 70 putts and 2 related to the second 70 putts taken in each condition. Panel B compares difference in performance across the testing sessions using the140 putts and Control/QE1 related to Study 2a and Control2 and QE2 relate to the findings from this study. The regression revealed no differences in slope but a significant difference in elevations (p < 0.001), suggesting different learning effects.

6.3.3 Does QE duration link to performance?

As shown in Figure 47, the best performance recorded was in the control condition at time bin 1000-1500ms and QE durations >2500ms were less effective for performance. To explore if the QE intervention improved performance a repeated measures ANOVA with factors of condition (2) * time (7) was conducted. As shown in Figure 47, there was a significant interaction [$F_{(2.283, 27.392)} = 17.104$, $p < 0.0001$, $n^2 = 0.330$]. There was a significant main effect for time [$F_{(2.851, 34.208)} = 9.602$, $p = 0.001$, $n^2 = 0.194$]. However, critically there was no main effect for condition, [$F_{(1,12)} = 0.881$, $p = 0.367$, $n^2 < 0.001$], with a similar success rate (64% for QE intervention and 62% for control mean difference of -0.314 % *SE* = 0.335), suggesting that the increase in trials with longer duration did not improve performance in comparison to the control condition, questioning the feasibility of QE intervention training.

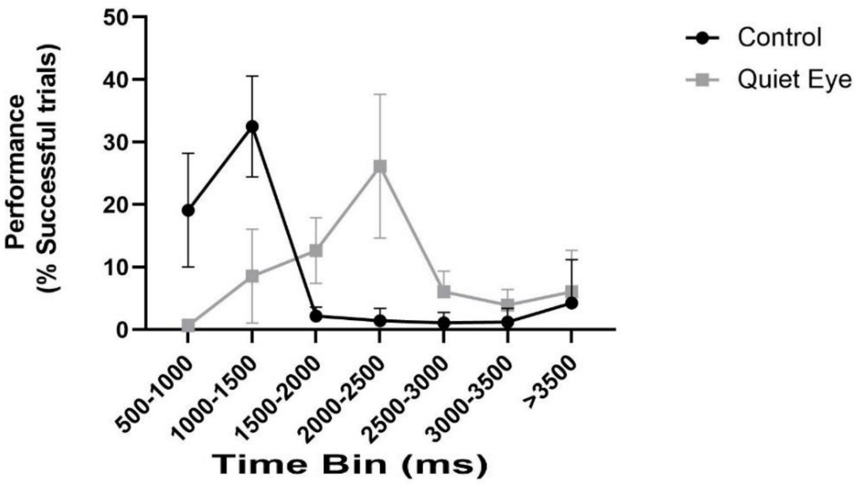

Figure 47. Difference in performance (successful percentage trials in ms time bin) for each condition (95% CI). Findings revealed that QE intervention training (grey square and line) did not improve performance in comparison to the control condition (black circle and lines).

6.3.5 Do Kinematics vary over multiple testing sessions?

To explore if there were any differences in kinematics, between the two days, on testing, key variables for the SAM PuttLab, namely tendency, timing, consistency and overall rating, were compared. Paired *t*-test revealed no significant differences between Day 1 and Day 2 for all variables except consistency (Figure 48). There was a significant difference in consistency between Day 1 and Day 2 ($t_{(175)} = 2.5$, $p = 0.04$), suggesting there is a difference in stroke kinematics when increasing the number of testing days.

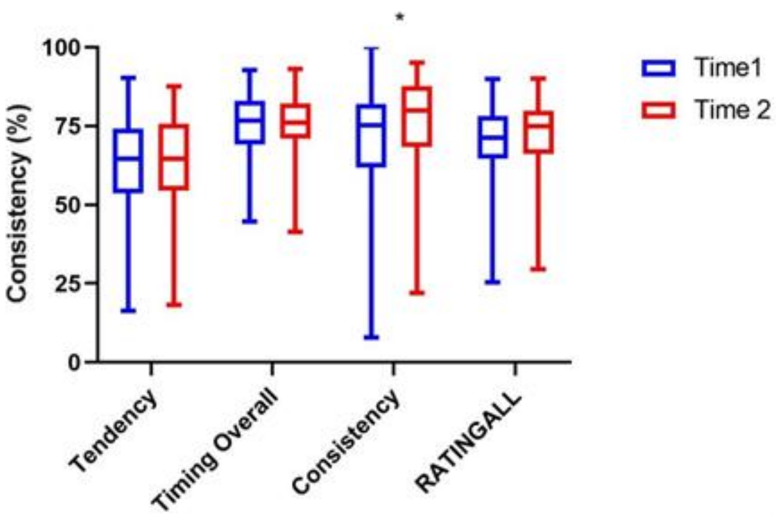

*Figure 48. Difference in kinematics variables taken from SAM PuttLab on Day 1 (blue) and Day 2 (red). The higher % consistency rating is representative of higher skilled. % score of >75 is indicative of Tour Pro, * = p<0.05, ---- represent mean and 95% CI).*

6.4 Discussion

The current study was designed to examine the impact of a QE intervention on golf putting performance and to address the design limitations from Study 2a. Consequently, 15 golfers took part in a within participant design study to examine the impact of a QE intervention on performance. Results revealed that consistent with the predicted hypothesis, QE intervention training did significantly increase QE duration in putts taken following the intervention in comparison to the putts taken in the control condition. In this present study, participants did demonstrate an increase in gaze behaviour in accordance with the QE intervention instructions (Vickers, 2007) so it could be concluded the QE intervention was successfully applied. However, consistent with Study 2a when analysed on a trial by trial basis, participants did not look at the ball for 2-3 seconds prior to initiating the putter before every trial. In the QE condition, when the participants did look at the ball for 2-3 seconds, they were more successful than the same time period in the control condition. Although when taking into consideration the other time windows, performance was not superior following the QE intervention. Findings from the control condition demonstrate that highly skilled golfers have developed expertise without adopting optimal QE duration. These findings question why you would teach a highly skilled golfer a QE intervention, especially when it would require a change from 'typical' gaze behaviour, without any clear performance benefit.

Unlike in Study 2a, other gaze behaviors (such as viewing time prior to the ball before QE and average fixation) did not change following the QE intervention. These findings illustrate some of Williams (2016) concerns regarding lack of knowledge surrounding what the QE intervention is actually training (Williams, 2016), especially without an underpinning theory explaining why longer QE duration is effective for performance. Our findings do question the efficacy of optimal QE duration in literature, particularly as < 2000ms still led to participants being able to successfully putt the ball and taken on a group level performance was not improved following the intervention. The rate of progression, did not vary across the four conditions, suggesting that when using this design with testing sessions one week apart, the progression rate was similar for all conditions and there were limited practice effects. Thus suggesting any performance benefit, we found in Study 2a was likely to be as a result of practice. These findings do pose several challenges to the current QE theory and suggest understanding the role of perceptual- cognitive expertise in golf putting goes beyond QE alone. To explore QE from a multi-faceted approach and to develop greater understanding of the features of perceptual-cognitive expertise in golf putting future studies in this thesis will consider the wider role of the environment and task. We will expand the focus from the QE duration and consider all phases of the golf putting routine (the pre-motor evaluation phase, the motor phase, and the post-motor phase, for more information see introduction). Furthermore, researchers have recommended taking an interdisciplinary approach capturing performance data via gaze, movement coordination, psychological state, neural activity to understand which other factors influence performance (Farrow & Panchuk, 2016). For example, in the present study our findings revealed stroke kinematics varied, over the two days of testing and this is something future studies employing multiple days of testing need to be aware of.

The findings also revealed a high level of variation and individual differences in performance and QE duration. These findings provided further support for the use of the "*individualised, process-oriented approach*" (Davids & Araújo, 2016, p. 3) to effectively support individuals to improve their performance. On this basis it could be argued that the use of group average or repetitive putt scores are not appropriate as it does not seem "group interventions" are effective even within a group of highly skilled golfers. Continuing to explore expert performance *in-situ* would help to establish the interaction between the individual, the task and the environment and help to provide a framework to guide practitioners in this area to establish how experts develop perceptual-cognitive expertise.

The main strength of this study is that replication of study design and exploration of QE duration on a trial by trial basis have enabled the researcher to gain a greater understanding of the complexity of the impact of QE duration on performance. The collective studies that combine to form Study 2 have enabled us to question the efficacy of a QE intervention for performance. They also help us to explain our findings from Study 1 i.e. highly skilled golfers do not typically have optimal QE duration without training and success is not associated with a longer QE duration. Furthermore, the findings from Study 2 offer insights towards explaining some of the reported inconsistencies found when trying to apply optimal QE duration in practice. The main limitation of this study is that variability within swing kinematics did influence performance. Moving forwards, it is important further research is completed into how variable golfers are in their swing consistency.

6.5 Conclusion

To conclude, findings suggest when practice is accounted for, there is no performance benefit following a QE training intervention. The studies within this thesis so far have demonstrated that understanding how QE duration is linked to performance is more complex than first thought and do not support the notion that a longer QE duration leads to greater performance and question why you would train someone in a QE intervention. Prior to disseminating findings to the applied field, considerations regarding methodological constraints (e.g., task set up) and differences between group averages and individual trials are important to acknowledge, particularly in relation to the efficacy of transfer. Furthermore, other factors that influence perceptual-cognitive expertise, such as consistency in movement and green reading may also impact on performance. For example, green reading may influence performance, as performance in the representative task design (Study 1, Chapter 3) was lower than performance on repetitive straight putts (Study 2a and Study 2b, Chapter 4 and 5 respectively). The impact of green reading will be explored in Chapters 7,8 and 9.

Chapter 7: Study 3a - Exploring Perceptual-Cognitive Expertise in golf putting

Study 3 consists of two parts: a screen-based task (3a) and a follow up behavioural study (3b) with two testing time points. These studies were designed to be exploratory in nature, given the limited literature in perceptual-cognitive expertise in golf putting (Carey *et al.* 2017). For a review of the ten studies in this area please see the chapter published on Perceptual-Cognitive Expertise in Golf Putting by Carey *et al.* (2017). The explicit aim of this series of studies was to develop further understanding of the perceptual-cognitive phase in golf putting and how green reading ability is related to outcome and expertise. It is intended that the findings from this study, will be used to inform the design of a perceptual-cognitive intervention to improve performance in Study 4 (Chapter 9).

7.1 Introduction

Research has suggested the type of putt (straight or sloped) can influence success rate. For example, Wilson and Pearcy (2009) found performance on 3m putts was significantly worse on sloped putts - severely-breaking (11% success) and moderately-breaking putts (41% success), than on straight putts (51% success) in University level golfers. In addition, to slope, we found when examining performance rates in Study 1,2a,/b in this thesis that task design can influence performance, with increased repetition (and practice) leading to a greater performance. Taken together, these findings highlight to understand golf putting performance, the task must include slope and varying putt locations, to distinguish how the golfer makes decisions on the best strategy to use when putting.

When deciding on the best strategy, the golfer ‘reads’ the green, to assess the optimal path from the ball (putt location) to the hole, taking into consideration the slope, break, and green contours (Campbell & Moran, 2014; Kenyon, 2008). Once the golfer has decided on their ‘read’ (intended aim line and pace) they need to set up their putting stance to be able to execute the chosen putt (van Lier et al., 2011), consistent with perception-action coupling (Bertenthal, 1996; Thelen, 1990; von Hofsten, 1993). Currently, knowledge on where a golfer looks, what visual information they process when they are scanning the green and the influence on putting set up is under-explored in the research (Carey et al., 2017; Craig et al., 2000). Therefore, the purpose of this chapter is to explore the underpinning cognitive processes associated with the perceptual-cognitive phase of putting.

In the limited research conducted on green reading (for review, please see Carey et al., 2017) there is growing evidence to suggest there are expertise based differences in ability to read the green. Pelz (1994) found from a sample of more than 179 amateurs, 128 club professionals, and six professional tour players; professional tour players were 2% more accurate than club professionals and 5% more accurate than amateurs when predicting break from a ball roll. Furthermore, Pelz (1994) also found golfers who were more accurate at reading the greens had a different scan path and used different sources of information compared to less skilled green readers. This is supported by innovative research conducted in a more controlled test of green reading, which found professional golfers were more accurate at reading the greens and they utilised different viewing positions, in comparison to elite amateurs and club golfers in a virtual reality environment (Campbell & Moran, 2014). Participants were asked to 'tour' the green using six set positions, then report precisely where they would aim to hole the putt. They were allowed six seconds at each position, following a circular route from crouching behind the ball to looking from the left side (standing), crouching behind the hole, standing behind the hole, looking from the right side, then lastly, standing behind the ball. Campbell and Moran (2014) found the professional golfers were accurate in reading 76.5% of putts, significantly higher than the accuracy attained by elite amateur and club golfers (57%). The main difference between the professionals and amateurs seems more related to how long information is processed rather than simply knowing the information sources to focus on. Both of these studies have methodological limitations due to the fact participants did not hit the putt. An examination of how behavioural markers of perceptual-cognitive expertise differ in real and virtual environments is needed to advance understanding in this area.

Another methodological consideration is the ability to appropriately understand the putting expertise of the participant, as different criteria have been applied when ascribing group labels. For example, across the ten studies reviewed in Carey *et al.* (2017), golfers classified as 'novices' range from those with no previous playing experience to those with a mean handicap of approximately 20. Similarly, the label 'skilled' has been applied to golfers ranging in handicap from 18 to 5.3 and 'highly-skilled' to groups with mean handicaps from 4.2 to plus 1.5. Critically, using handicap to determine skill level may be inaccurate as handicap reflects all aspects of golf play, so may lack sensitivity as an indicator of putting expertise. Furthermore, in Study 1 (Chapter 3) detailed in a published abstract, Carey *et al.* (2016) found handicap was a poor predictor of putting expertise in a putting task when recruiting fourteen golfers, comprised of 5 professional (Age M = 34. 4 ± 5.2 years) and 9 elite amateurs (Age M = 24.1 ± 7.5 years), handicap range -2 to +5, (M = +1.3 ± 1.9). In contrast, consistency in stroke kinematics, namely, impact spot and clubface angle rotation where found to be better predictors of performance as participants displaying less variability on these measures holed more putts than those who displayed higher variability. Therefore, suggesting kinematic variables may provide a more sensitive measure of putting ability than golf handicap. Therefore, to further understand expertise, there is a need to profile the golfer on current playing hours, number of playing years and performance markers from the last year, namely greens in regulation and average putts per round. Typically, these measures are not reported in literature, but having more detailed knowledge about practice and playing experience would provide additional information that might help researchers better delineate participants, and help to understand differences in perceptual-cognitive expertise across the expertise spectrum.

To increase knowledge on where a golfer looks and what visual information they process when scanning the green and 'reading' the putt, a screen-based task was developed to recruit a large sample of golfers (including gathering profiling information). It is not clear at this stage whether a 2D flat image is sensitive enough to measure differences due to expertise and if the same perceptual cognitive skills are used when viewing a computer screen or in the real world. A behavioural study where the golfers actually hit the putt has been designed as a follow on from the a screen-based task (Study 3b). A secondary aim is to establish if golfers can make accurate judgements on how the ball roll influences the putt outcome via observing a video and to establish if there is a similar or different decision-making process during the behavioural study. It is hypothesised that expertise will impact on the ability to accurately read the green using a 2D image and predict ball roll on videos.

7.2 Methodology

7.2.1 Participants

Eighty-two participants (50 male) completed an online screen-based task in a mean duration of 3.6 hours with 38% of participants. Average age for the males was 50.7 years ±18.2 and 58.2 years for females ± 12.1. Participants had an average playing experience of 28 years ± 18.6 and on average currently played in competitive golf for 10.6 hours per week ± 12.6. Five of the participants were professional, with two of the participants playing or having previously played on the European Tour. Average handicap was 8 ± 14.5, average putts for all participants was 36.9 putts ± 0.7, average green in regulation was 51.4% ± 54.3%. Participants spent on average 2.7 hours watching golf per week on the TV ± 3.04 and self-rated green reading ability varied from not skilled to very skilled on a Likert scale (1= not skilled, 5 = very skilled). Twelve of the participants rated themselves as unskilled, 28% rated themselves as somewhat skilled, 24% rated themselves as skilled, 24% rated themselves as moderately skilled and 12% rated themselves as very skilled.

7.2.2 Protocol

A pilot screen-based task was conducted using a range of golfers and golf coaches (*n* = 15) who were local to the lead researcher. The questionnaire was modified according to feedback from the pilot screen-based task. The modifications were to the anchors for the estimation of pace and in the addition of a picture as a guide to show the intended path in the video section. Ethical approval was granted by the University of Stirling Psychology Ethics Committee. All procedures were in accordance with the Declaration of Helsinki ethical principles for collecting research with human participants. An online screen-based task (Appendix 2) was developed through Qualtrics Software (Qualtrics, Provo, UT) and an online link was distributed through the National Governing Body and local golf club member pages. The information sheet and informed consent form were embedded into the screen-based task and participants were unable to complete the screen-based task if they did not provide consent. The screen-based task consisted of five main sections; 1) consent form, 2) demographic section, 3) viewing of two putts to asses read to read location information, 4) viewing of five videos to assess outcome and finally 5) debrief.

In Section 3 the participants viewed a photograph of a hole and were asked to indicate what they thought the read of the putt was from a range of options (straight level, straight uphill, straight downhill, R-L level, R-L uphill, R-L downhill, L-R level, L-R uphill, L-R downhill). Participants were then asked to rate their intended pace to hit the putt based on their read using a sliding scale (0 [lag into the hole] -1 [hit the back of the hole at pace]). The participants were then asked to mark their intended aim on a line through the hole and select using clicks on the picture the path they intended the ball to take. Participants were then asked to rate how confident they were in their read using a Likert scale (0 [not confident] to 5 [very confident]). Participants were then given a choice of six positions to view the putt from, based on Campbell & Moran (2014) as part of their pre performance routine, including capturing timing information at each viewing location, and then asked to rate the perceived effectiveness of each viewing location in terms of helping them make a decision on the read of the putt (using a Likert scale from very useful to did not view the position). Participants were then given an opportunity to review their initial read, pace information and update their aim point and intended path, based on the further information gained from viewing the putt in the different locations. Participants were then instructed to watch a video of a professional golfer hitting the putt and asked to confirm if they still believed their read to be true or given an opportunity to change their read based on what they had seen in the video. This process was repeated for a second putt (that is a different type of putt).

Section 4 was split into two tasks (a and b); in task a, there were six videos whereby the participant had to select whether the ball was going to hit or miss. The video was edited so the participants could not see the outcome of the putt. Before answering the question on whether the ball was going to land in the hole or not, participants were instructed to view a video of the putting path for both the maximum and minimum pace for that putt, to provide perceptual information about that surface intended to act as a guide. After watching the six videos (task a), participants were finally asked to watch three further videos (task b) of a professional golfer hitting a putt. In this task, participants were asked to select what read they thought the putt was from a range of options (straight level, straight uphill, straight downhill, R-L level, R-L uphill, R-L downhill, L-R level, L-R uphill, L-R downhill). The videos were the same putt taken from three different angles, from behind which is not allowed in competition golf, from the side and from the side delayed. The side angles were designed to recreate the view when watching an opponents' putt. It is of interest to see if viewing location influences the participant's decision on type of putt.

7.2.3 Statistical Analysis

Priori alpha level of significance was set at $p < 0.05$. Data presented as mean and 95% CI. To explore if there is a relationship between perceived green ability and average putts per round green reading ability, a Spearman's rank order correlation coefficient (i.e., Spearman's rho) correlation was conducted. To assess differences in correct responses based on average putts per round an Independent-Samples Kruskal-Wallis test was conducted. Significant differences were further analysed using Dunn's multiple comparison post hoc test and Bonferroni correction was applied. To explore if viewing location changed between putt 1 and putt 2 chi square analysis was completed. To assess differences in viewing location and perceived effectiveness based on correct responses an Independent Samples Mann Whitney U *t*-test for each putt separately was used. Differences in correct response for in predicting ball roll based on average putts per round was compared using an Independent Samples Mann Whitney U *t*-test.

7.3 Results

7.3.1 Section 2 - Demographic section

Skill level: Participants were asked to report their perceived green reading ability (1 not at all skilled and 5 very skilled) and their average putts per round (measure of putting skill). The descriptive statistics (Table 11) show that perceived skill level in green reading is related to skill level (average putts per round), with those who have less perceived ability having higher average putts per round in comparison to those participants who have higher perceived ability and fewer putts per round.

Table 11. Average putts per round based on self-rated skill level in green reading.

Description	Percieved Skill Level	Av Putts Per Round	*SD*
Not all skilled	1	39	3.00
	2	37.63	4.93
Skilled	3	37	3.87
	4	36	5.04
Very skilled	5	29	2.00

There was a significant negative relationship between perceived green reading skill and average putts per round ($r_s(82) = -3.81$, $p = 0.026$) with average putts per round decreased as perceived green skill increased. Thus highlighting the more skilled golfers also perceived their green reading as more skilled than less skilled golfers.

Green reading frequency: Participants were more likely to read the green in competitions compared to practice. However, one participant reported they did not always read the green prior to putting, even in competitions. There was no difference in green reading frequency in competitions based on the number of years the golfers had been playing golf (H = 1.2, df = 2, p = .549). There was no difference in green reading frequency in competitions based on the average putts per round (H = 4.64, df = 2, p = .098). The data (Figure 49) highlighted, with the exception of the one participant who did not read the green at all during competitions, the golfers who were more skilled tended to read the green more (every putt rather than often) in comparison to the lesser skilled golfers during competition.

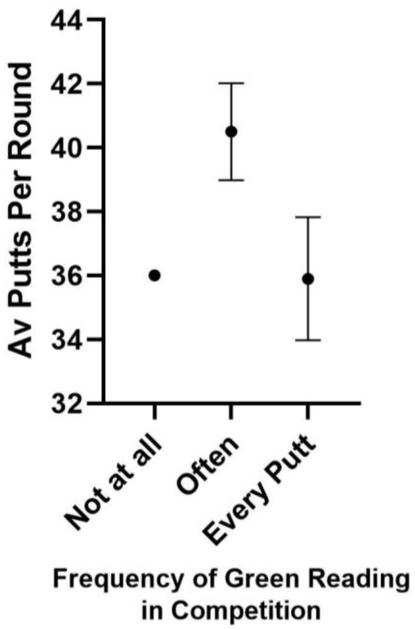

Figure 49. The frequency of green reading in competition as a function of average putts per round (95% CI). A lower average putt per round indicates a higher skilled golfer, and with the exception on one participant higher skilled golfers tend to read the putts more in competition than less skilled golfers.

To improve green reading skills, 24% of participants did not do anything, 5% did not know what they did and the remaining participants use a range of 34 strategies, with the most commonly cited including practice, taking a lesson, reading or watching YouTube and using aimpoint. For more information please see Figure 50 below.

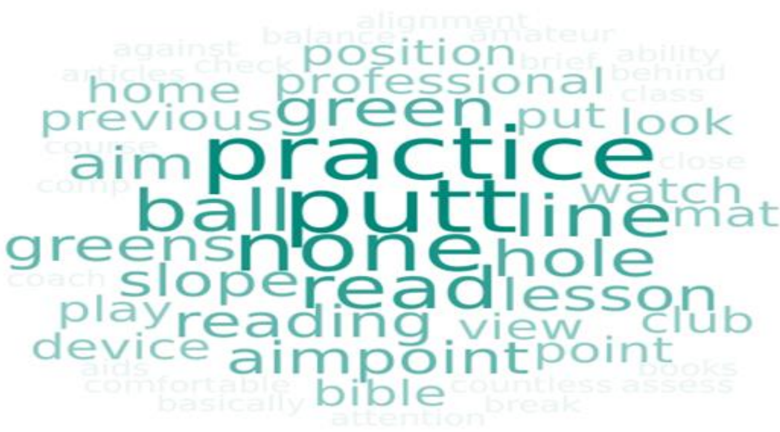

Figure 50. Word cloud describing activities/strategies that golfers do to help them to read the greens.

Participants were split into groups based on the strategies they use i.e., no strategy, one strategy, two strategies and greater than 3 strategies. As shown in Figure 51, lowest mean average putts per round was associated with 3 or more strategies, however there was no differences in average putts per round based on strategies used (*H* = 2.4, *df* = 3, *p* = 0.494).

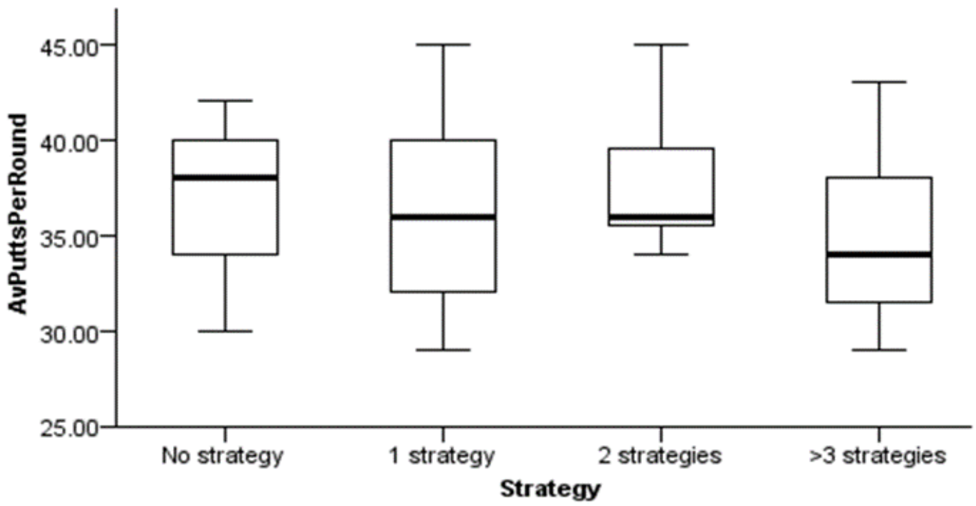

Figure 51. Average putts per round as a function of number of strategies used to improve green reading skill (ranging from no strategies to more than three). Black line indicates the mean and the error bars are 95% CI.

7.3.2 Section 3 - Viewing 2D images of putts

Green reading in practice: The third section required the participants to view two different putts. In the first putt 34.2 % participants were able to identify the correct putt and in the second putt 37% of participants were able to identify the correct putt after the initial read. In the first putt participants' responses to the type of read varied from straight level (5.7%), straight uphill (2.7%), straight downhill (8.6%), L-R level (22.8%), L-R uphill (5.7%), L-R downhill (34.2%), R-L level (2.7%), R-L uphill (5.71%) and R-L downhill (11.4%). In the second putt there was less variation in responses with participants choosing straight level (33%), straight uphill (7%), L-R uphill (3%) L-R downhill (3%), R-L level (27%), R-L uphill (37%) and R-L downhill (20%). In both cases the highest number of participants selected the correct response, however, there was not consistency across the participants. Correct responses for the two putts (i.e., 0/1/2) were recorded for each participant.

Correct responses did not differ based on experience (H = 1.4, df = 2, p = .495) Furthermore, as shown in Figure 52 there were no differences in average putts per round (H = 0.82, df = 2, p = .960) between those participants who scored 0% (no correct answers 57.1% of participants), 50% (1 out of 2 putts correct, 25.7% of participants) and 100% (both putts correct, 17.1%) meaning skill level (actual [averaged putts per round]/perceived [self-selected green reading ability]) and experience (years played) could not be attributed to correct responses.

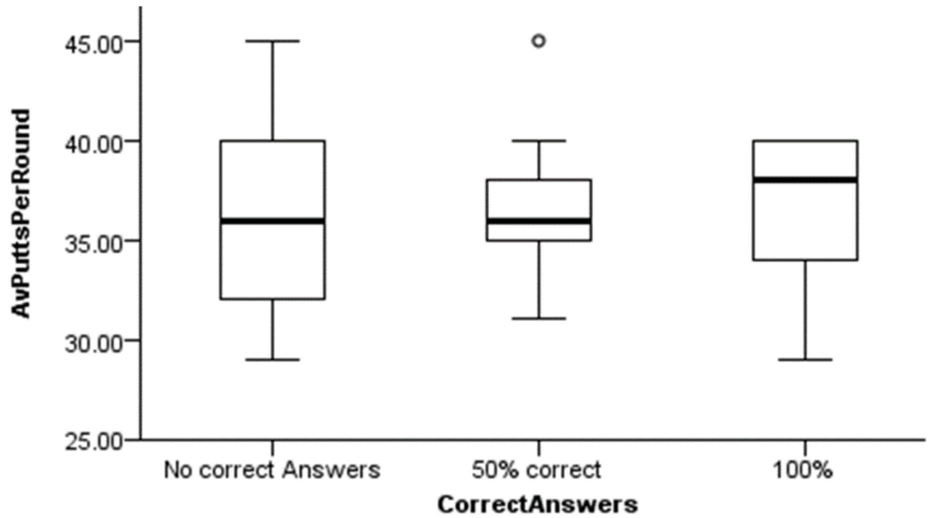

Figure 52. Average putts per round as a function of ability to correctly identify the read of both putts (including no correct answers, one correct answer [50%] and two correct answers [100%]). Black line indicates the mean and 95% CI are shown. The outlier participant is represented with a circle. Skill level (lower average putts per round) is not related to getting 100% correct.

The putts in Section 3 varied, therefore it was of interest to see if the participants used a different viewing strategy based on the different types of putts. There was not a significant difference in viewing location between putts, χ2 = 2.700, *df* = 5, *p* = 0.746 (Figure 53).

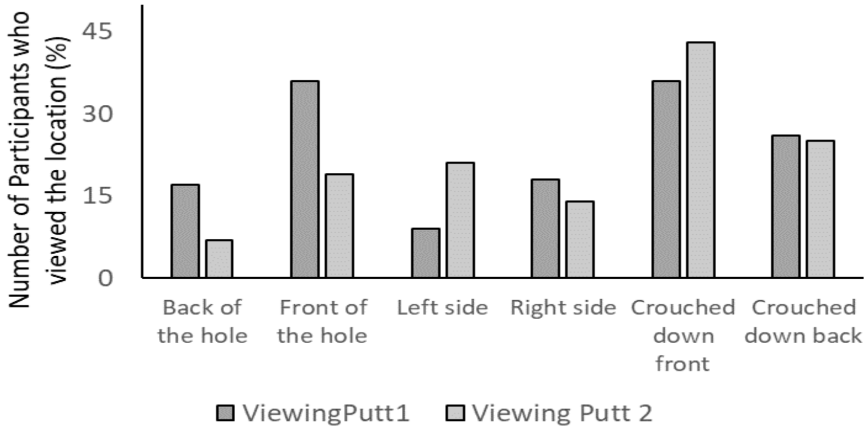

Figure 53. Differences in viewing locations chosen to help read the putt for putt type 1 and putt type 2 (Putt 1 is L-R downhill and Putt 2 R-L uphill). There was no differences in viewing locations chosen despite the putt being different.

There were no differences in the outcome of the putt (correct response selected) based on viewing location; back of the hole putt 1 (*U* = 97.5, *p* = 0.845), front of the hole (*U* = 97.5, *p* = 0.556), left side (*U* = 97.5, *p* = 0.499), right side (*U* = 97.5, *p* = 0.245), crouched down front (*U* = 97.5, *p* = .845), crouched down behind (*U* = 97.5, *p* = 0.303) for putt 1. There was a tendency for differences in perceived effectiveness based on outcome (correct response selected) for putt 1 for the location of back of the hole 1 (*U* = 60, *p* = 0.066), with a correct response associated with higher rated perceived effectiveness. There were no differences in perceived effectiveness based on outcome of the putt (correct response selected) for putt 1 at the other viewing locations; front of the hole (*U* = 60, *p* = .909), left side (*U* = 60, *p* = .647), right side (*U* = 60, *p* = .450), crouched down front (*U* = 60, *p* = .845), crouched down behind (*U* = 60, *p* = .303).

For putt 2, there were no differences for viewing location chosen and outcome (selection of accurate putt); back of the hole (*U* = 97.5, *p* = 0.767), front of the hole (*U* = 62.5, *p* = 1.00), left side (*U* = 62.5, *p* = .703), right side (*U* = 62.5, *p* = .471), crouched down front (*U* = 62.5, *p* = .497), crouched down behind (*U* = 62.5, *p* = .134). Similar to putt 1, there was a tendency for differences in perceived effectiveness based on outcome (correct response selected) for putt 2 for the location of back of the hole 1 (*U* = 60, *p* = 0.07), with a correct response associated with higher rated perceived effectiveness. There were no differences in perceived effectiveness based on outcome of the putt (correct response selected) for putt 1 for the other locations; front of the hole (U = 60, p = .094), left side (U = 60, p = .899), right side (U = 60, p = .933), crouched down front (U = 60, p = .832), crouched down behind (U = 60, p = .497).

It is also of note that for putt 1 after viewing more information, 71% of participants agreed with their original read and chose to change their aim point and putter path (Figure 54). However, for putt 1, at the initial read, there was not clarity in the intended aim point with participants selecting both sides of the hole and there was not a clear consensus on putting path. The confusion seemed to get worse when the participants viewed more information and our findings support that viewing location, timing and perceived effectiveness is not related to putting accuracy for putt 1. For putt 2, 96% of participants opted to stick with their initial read and did not choose to change their read based on further viewing information. At the initial read, participants were able to select the correct aim point and putter path. This is an interesting finding as the participants seemed to know what putt they wanted to hit, even if they could not all identify the correct read type.

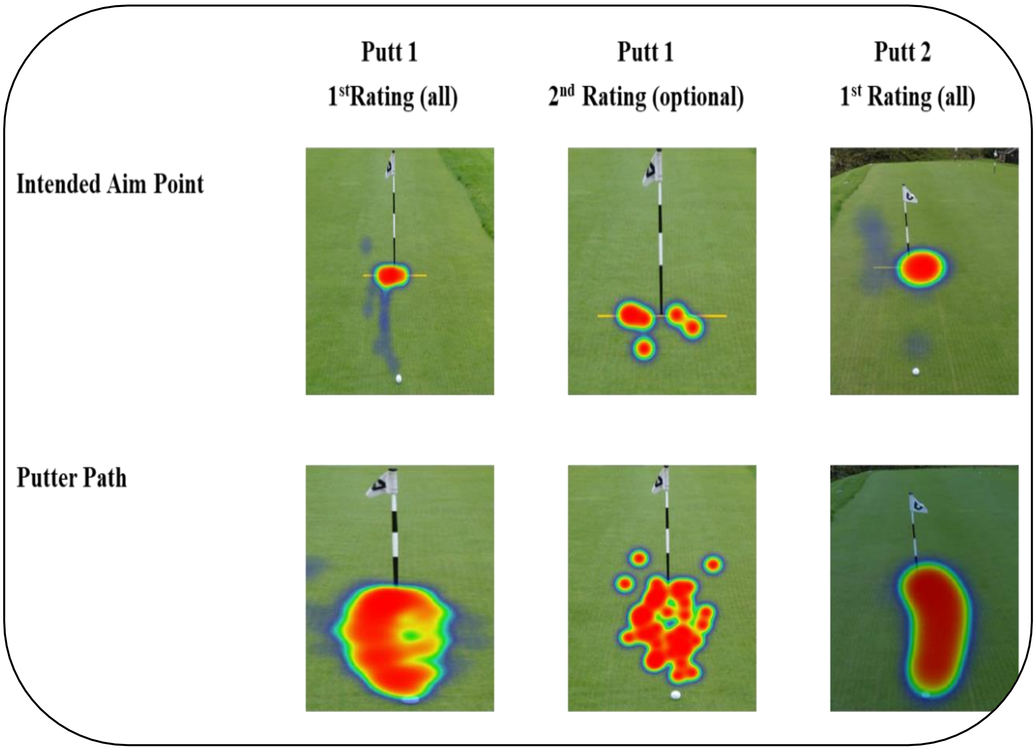

Figure 54. Participants selected intended aim point and putter path for both putt 1 and putt 2. For putt 1, in the 1st and 2nd (optional) rating participants choose an aim point both sides of the hole and there was not clarity in the direction the participants intended the ball to travel. Not all participants chose the correct aim point and/or path. For putt 2, no participants opted to change their read based on further information and all participants chose the correct aim point and path at the initial read. There were differences in ability to select the aim point and path across the two putts, however, there was little difference in participants being able to select the correct read (34% at putt 1 and 37% of participants at putt 2).

As shown in Figure 55, there was a significant difference in correct responses after watching the video of the professional golfer hit the ball, based on average putts per round (H = 6.903, df =2, p = .032) between those participants who scored 0% (no correct answers 37.1% of participants), 50% (1 out of 2 putts correct, 34.3% of participants) and 100% (both putts correct, 28.6%). There was a significant difference in average putts per round between those who got 50% correct in comparison to 0% correct, with those who got 50% correct having a lower average of putts per round score (more skill), p = 0.32 in comparison to those participants who got 0% of correct answers. All other comparisons revealed no differences. There were no differences in perceived green reading ability and accuracy after watching videos (p = .390).

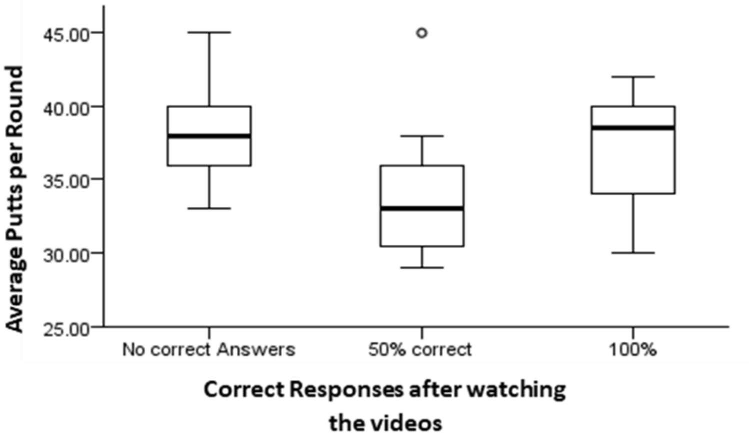

Figure 55. Average putts per round as a function of being able to correctly identify the put after watching the video (including no correct answers, one correct answer [50%] and two correct answers [100%]). Black line indicates the mean and 95% CI are shown. The outlier participant is represented with a circle. Skill level (lower average putts per round) is not related to getting 100% correct.

7.3.3 Section 4 - Viewing of five videos to assess outcome

Section 4 involved participants watching videos to predict the outcome of the putt. The data highlighted the more highly skilled golfers (who had the lowest average putts per round) did accurately predict the outcome based on the video (Figure 56). However, when considering the whole sample, an Independent-Samples Kruskal-Wallis test did not find any differences in average putts per round based on number of correctly identified videos (H = 9.24, df = 5, p = .100).

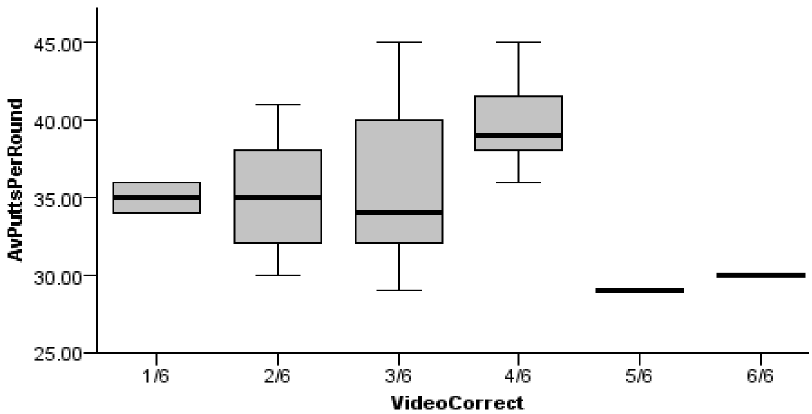

Figure 56. Average putts per round as a function of being able to correctly identify the outcome of the putt after watching the video (based on the number of correct answers 1:6). Black line indicates the mean and 95% CI are shown. Golfers who can correctly identify five and six videos are considered to be higher skilled based on their average putts per round, however, there is not an overall difference based on skill level.

When watching the same putt from three different angles, only 41% of participants could read the correct putt and then identify that all three putts were the same. There were no differences in average putts per round between those who accurately identified the putt and those who did not (U = 23.5, p = .270). These findings suggest it is important to understand what viewing position that the participant is viewing the putt from, as it will change their perception of what the read is. If the participant is only able to see the opponents view, then any green reading training will need to account for the change in location and perception.

7.4 Discussion

The present study aimed to gain further understanding of the underpinning differences in how golfers read the green, including which information sources they use to help them to make a decision, across a range of experienced golfers of variable skill levels. Participants who have less perceived green reading ability (i.e., rate themselves 1 out of 5) have higher average putts per round in comparison to those participants who have higher perceived green reading ability (i.e., rate themselves 5 out of 5) and take fewer average putts per round. Although, when considering participants who are in the 'middle' (rate 2-4) the relationship with average putts per round is less clear. These findings are useful to consider when doing applied interventions for green reading, as it cannot be assumed that perceived green reading skill is related to skill level in terms of average putts per round, unless at the extremes of not at all and very skilled.

Interestingly, there was also variation in how often participants used green reading on the course during practice and competition. Participants used green reading more during competition in comparison to practice with most participants choosing to read the green for all competition putts. At this stage, it is unknown why the golfers do not read the green for every putt and whether the choice not to read the green was related to the putt type, distance or familiarity of putting on a home course. In terms of practicing green reading, there was a large variation in the types of activities the participants did, ranging from nothing to specific practice, instruction from coaches and embedded practice as part of pre-shot routines. The findings revealed there were no differences between the number of strategies used based on average putts per round. Although, participants who use the most strategies (3 or more) had the lowest mean average putts per round, and participants who used no strategies had the highest mean average putts per round, thus suggesting once a golfer had developed a strategy, having a consistent strategy was more beneficial for performance.

One of the aims of the screen task was to explore green reading expertise in practice by asking participants to read a 2D image. The findings revealed that participants could accurately read the green from a 2D image, however, inconsistencies in the accuracies of the green read across the participants and the different putt type existed, although these differences were not related to expertise. The lack of expertise related difference is inconsistent with previous research into green reading which found tour professionals to be more accurate at reading the break, in comparison to amateurs (Pelz, 1994). These differences may be due to the 2D image as it does not provide all the characteristics which are available *in-situ*, so may limit the ability for this test to accurately assess expertise in relation to green reading. This is supported by research by Campbell and Moran (2014) who did find expertise differences in green reading using a single putting green displayed in virtual reality. Therefore, further research should take place *in-situ* or with a 3D environment to enable the golfer to use all the sources of information available to them when putting in competitive golf in order to truly research and understand expertise differences (Dicks et al., 2010).

Although there were no expertise differences when using the 2D image, we did find differences in the processes the participants used when reading the green. Participants differed i) in their choice of and number of viewing locations accessed; ii) time spent viewing the location; and iii) perceived effectiveness of the location information for each putt. Participants rated the back of the hole view as the most useful for informing their decision about the read and there is a positive trend between perceived effectiveness of viewing location and the selection of the correct response. In addition, there was also an increase in time spent viewing location information for putt 1 in comparison to putt 2, however, this did not seem to improve decision making as the ability to identity the correct read was lower for putt 2 in comparison to putt 1. We also found no expertise based differences in time spent viewing the locations. Our findings contrast with research suggesting expert golfers spend more time viewing the green prior to putting in virtual reality green reading environment (Campbell & Moran, 2014) than less expert golfers. Although in Campbell and Moran (2014) study their cohort did include more tour professionals (n = 17) than our current study. Furthermore, virtual reality is in 3D and the picture is in 2D and this may make a difference, especially given that when participants viewed a video of someone hitting the putt they were more able to correctly read the putt in comparison to their initial read.

Our findings suggest a 2D image does not provide sufficient information that experts can use to their advantage to read the putt, therefore we recommend that an image is not used as a training aid or in research (Araújo et al., 2006) . In contrast, findings suggest a video is suitable for measuring expertise based differences, as the highly skilled participants were able to increase their accuracy in response to watching video stimuli in comparison to the less skilled participants. These findings suggest that use of virtual reality and video can be used to enrich learning and increase practice opportunities (Stone et al., 2018). The increase in accuracy/performance as a function of expertise, does highlight experts are more able to use the perceptual information in the environment, as a video does provide extra perceptual information for example, information on the ball roll, that is not present in a 2D image. Although, further work is needed in this area as there was a difference in average putts per round between those who scored no correct answers (higher average putts per round) in comparison to those who scored 50% correct answers, but not between 0% and 100 and 50% and 100%.

The highly skilled golfers were more able to identify the outcome of the putt (correct answer in 5/6 videos out of 6), in comparison to less skilled golfers, by tracking the ball and predicting the outcome using information in the environment. However, there were no differences on a group level particularly since participants who could correctly identify the outcome in 4 out of the 6 videos had the highest mean average of putts. Furthermore, the complexity of understanding the green reading process was also highlighted in the fact participants could identify the right aim point and putter path but not necessarily the right putt type. For example, in putt 2, all participants could identify the correct aim point and path but only 37% of participants could identify the correct read. We suggest the relationship between green reading and expertise is complex and further understanding in this area is required. Specifically, to understand which sources of information golfers are viewing when they make a correct decision and how this differs to an incorrect decision and how this relates to overall expertise level.

On a practical level, when considering the implications of reading an opponent's putt in practice during competitive golf, our findings suggest when a putt is viewed from an opponent's perspective only 41% of participants can correctly identify the read of the putt. This has significant implications from an applied perspective, as golfers are not allowed to stand behind an opponent's putt (only their own), so for the transfer of learning from their opponent's putt to their own to be effective, it is important to understand whether the golfer is able to read the putt appropriately from the side position, otherwise they may misinterpret the additional information from their opponent's putt. It also reinforces how the removal of key visual information can hinder perception and action and associated expertise (Stone et al., 2013).

The screen-based task provides an indication of which factors can contribute to green reading expertise. It appears that just being exposed to greens or being a highly skilled golfer does not automatically mean golfers have green reading expertise. The task has also started to help develop understanding of how green reading expertise is developed, potentially what the best way to measure green reading expertise is and the limitations of using a 2D picture image.

Limitations of this screen-based task is that participants do not hit the putt and the green reading is done via an image or a video of someone else hitting the putt thus reducing the action '*fidelity*' (Pinder *et al.,* 2011). Likewise, Gibson (1979), states "*perception is an invitation to act, and action is an essential component of perception*" (p. 46). In the future, studies need to be conducted *in-situ*, to allow a comparison between intended behaviour and actual behaviour to assess skilled perception (Araújo et al., 2006). A follow up study has been designed in Chapter 8 and the main aim is to explore if more highly skilled golfers read the green and evaluate their own putt more accurately than less skilled golfers.

7.5 Conclusion

To conclude, this screen based task highlighted that understanding green reading is complex. There were inconsistencies in green reading processes and in reads across participants. Video feedback, can provide some insight into participants' ability to use ball movement to correctly interpret characteristics of the green and path and this looks to be a useful avenue to explore further, along with participants actually hitting the putt in Study 3b (Chapter 8).

Chapter 8: Study 3b- Exploring Perceptual-Cognitive Expertise in golf putting over multiple sessions

8.1 Brief Overview

Research has highlighted that performance (successful putts holed) decreases, as the slope of the putt increases across all skill levels of golfers (Karlsen & Nilsson, 2008; Pelz, 1994; Wilson & Pearcy, 2009). The increase in slope increases the difficulty of the putt and to putt successfully the golfer needs to take into account the slope, break, and green contours (Campbell & Moran, 2014). The golfer takes in perceptual information about the slope, break and contours, as part of their pre-shot routine when 'reading' the green. In Carey *et al.* (2017) this phase has been operationalised as the perceptual-cognitive phase of golf putting. Currently, there is a lack of scientific literature exploring perceptual-cognitive expertise in golf putting (Carey *et al.*, 2017). To gain more information on green reading, a screen-based task was conducted in Study 3a (Chapter 7). In the screen-based task we found a high level of variation in the strategies the participants adopted to read the green. Critically we did not find any expertise differences in the strategies chosen or accuracy of the green when using a 2D image, but we did find expertise based improvements in evaluating the read and ball roll when using the videos.

Perceptual-cognitive expertise combines the ability to firstly, search for the right information at the right time (Mann *et al.*, 2007) and secondly, use this information to plan and select the most appropriate motor response (Marteniuk, 1976). However, Gibson (1979) has argued that perception and action is more complicated than conceptualising perception, as input and action, as output, despite the obvious connection between seeing and then doing. (Gibson, 1979) states perception and action are interdependent and mutually linked as *"we must perceive in order to move, but we must also move in order to perceive,"* (p. 223). In response, researchers are increasingly seeking to create tasks capturing the reciprocal relationship between athletes, task environment (Araújo et al., 2006) to understand skilled perception, including i) understanding the demands the environment places on an athlete's existing action capabilities (Dicks et al., 2009; Gibson, 2015); and ii) relationships between perceptual-cognitive skills involved and learning processes that follow (Bootsma, 1989; Davids et al., 2012).

Accordingly, the aim of this study is to develop greater understanding of perceptual-cognitive processes involved in putting *in-situ* to gain insights into the reciprocal relationship between golfers, task, and environment. More specifically, i) exploring whether golfers can accurately green read including setting up beforehand, ii) exploring whether there are any expertise based differences in green reading ability, performance, ability to evaluate the putt, stroke kinematics and lastly, iii) to see if the golfer and coach varied in their ratings. Furthermore, to increase the representative task design and ability to disseminate the findings, it is important to see how the environmental changes due to time of the year: summer and winter, putt type and expertise influence perceptual cognitive expertise.

8.2 Methodology

8.2.1 Participants

Eleven experienced golfers (6 males and 5 females, aged between 18 years and 68 years), including 5 amateurs (handicaps ranging from -25 to +5) and 6 professionals participated in the study. These participants all completed the screen-based task in Study 3a and were right handed, right eye dominant, and had normal or corrected-to-normal vision. Average putts per round were 33 putts ± 3.5 and average GIR was 50% ± 18.2.

8.2.2 Procedure

Ethical approval was granted by the University of Stirling Psychology Ethics Committee. All procedures were in accordance with the Declaration of Helsinki ethical principles for collecting research with human participants. The lead researcher contacted the Performance Director from the Scottish Golf Union for permission to speak to players matching the eligiblity criteria, to gauge interest in participating in the study, and head professional at Glenbervie Golf Club to see if any members would be interested in taking part in the study. The lead researcher then met interested players and members to explain the study requirements and related information. Following this meeting, all participants were asked to confirm involvement in the study by sending the lead researcher a signed copy of the informed consent sheet and demographic information. Players were made aware that participation was not a requirement, that it was voluntary without obligation, and that participation had no influence on training and selection. Furthermore, there was no coercion to participate from the Performance

Director, golf club, head professional at the golf club or any coaches or the lead researcher.

8.2.3 Protocol

Participants completed two testing sessions, one in the summer and one in the winter (see Figure 57). Winter greens are slower in stimp value (8 stimp) in comparison to 11 stimp value for the summer greens; stimp value is a measure of green speed, whereby the higher the stimp rating the faster the green). At each testing session, participants completed a 16 putt Sam PuttLab profile on an indoor surface before completing 12 competition putts outdoors. Before each putt, participants i) marked their intended aim with a tee in the ground that was visually checked by the coach and ii) rated their confidence in their ‘ability to read the putt’ and their ‘ability to execute the putt in line with their chosen read’ (out of 10- with 10 being very confident).

Following the putt, participants and coaches would independently assess whether the participant on five variables; 1) accurately read the green, 2) set up to the putt correctly, 3) hit the putt at the correct pace, 4) hit their intended aim point and 5) had a good execution. When assessing the putt, participants and the coach were asked to rate ‘Yes’ or ‘No’. In addition to observing the putt, the coaches could use kinematic feedback provided by Trackman to support their assessments. The participant could only use their own feedback and could not ask the coach for feedback.

In between each competition putt, the participant completed either a ball rolling task or a repetitive putt task from 5ft. Performance on the repetitive putt task was collated but no measures were taken on the ball rolling task. In both the ball rolling task and the repetitive putt task, the hole used was not used in the competitive putting task.

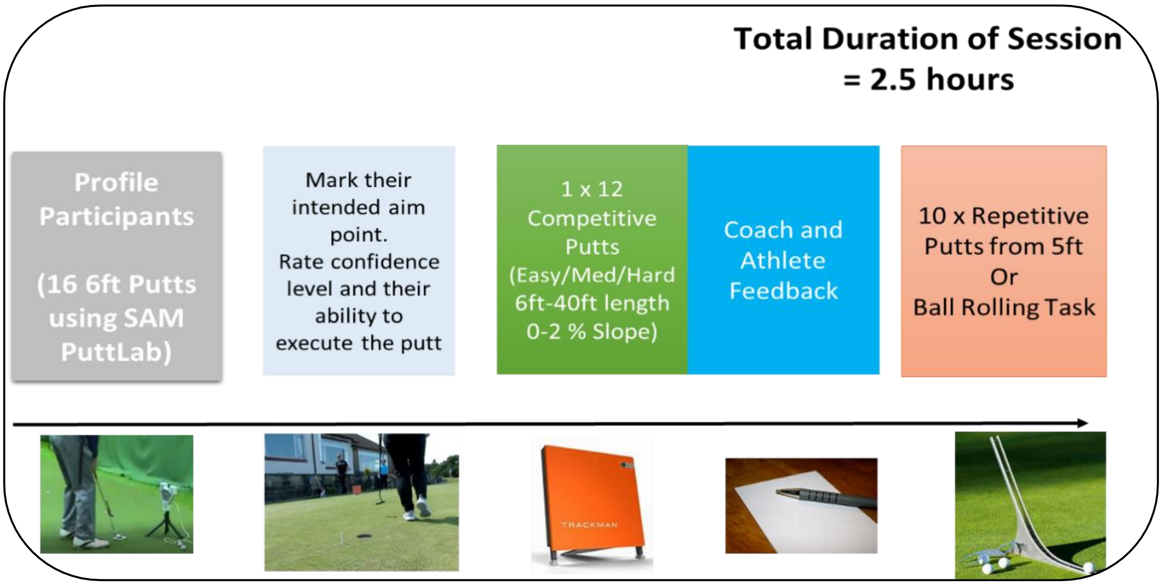

Figure 57. Schematic of Study 4.2 Methodology- example of one session.

8.3.4 Measures

8.3.4.1 Performance

Performance was assessed through the number of successful putts in the competitive putts (out of 12) and from the repetitive putt task (out of 60 x 6).

8.3.4.2 Swing Kinematics

Kinematic variables captured by SAM PuttLab technology (Marquardt, 2007). The two kinematics factors examined were Impact Spot consistency and Face Angle at Impact consistency (consistent with Study 1). Impact Spot is defined as the exact place where the ball contacts the putter (putter face) during the stroke. Impact Spot consistency highlights the variability in point of impact, with 100% being no variability and 0% being high variability. Face Angle at Impact consistency reflects how consistent the participant is at keeping the face relative to the target aim. A poor Face Angle at Impact consistency has been linked to visual perception problems. For both measures, a score of >75% consistency is indicative of an expert skill level (Marquardt, 2007). To assess these variables, sixteen repetitive putts were taken using SAM PuttLab on an indoor straight 12ft putt.

To explore changes in the representative task, TrackMan4 (Denmark) was used as it is able to cope with changes in the level of the surface through it’s calibration system. TrackMan4 uses a dual radar system providing accurate data for diagnosis and analysis of golf shots (Johansson et al., 2015). The aim point was calibrated during the set-up process for each putt (see Figure 58). Numerical information on ball speed, roll speed, club speed, forwardswing, backwards swing and tempo was collated.

Figure 58. Screenshot of the visual TrackMan4 data and set up during a summer testing session; the black line is the aim point (coach), the red line is the aim point (participant) and the blue line is the path the ball took.

8.3.5 Statistical Analysis

To assess differences in performance based on the putt task and time, a 3 (task design: indoor 12ft repetitive, outdoor 5ft repetitive and outdoor competitive 6-25ft) * 2 (time: winter/summer) repeated measures ANOVA was conducted. To explore whether there were any differences in performance based on putt distance and slope, a series of one-way ANOVA were conducted. Lastly, to explore whether there were any differences based on skill level, a mixed (within and between) repeated measures ANOVA, with the within factors of time (2 winter/summer) * putt type (repetitive/competitive) and the between factor of skill level (higher or lesser skill, based on median split average putts per round) was conducted.

To explore if there were any differences in the kinematic factors a mixed (within and between) repeated measures ANOVA, with the within factors of time (2 winter/summer) * kinematic variables (face aim consistency/impact spot consistency) and the between factor of skill level (higher or lesser skill, based on median split average putts per round). Additionally, separate paired sample *t*-tests was used to compare differences in roll speed, ball speed and club speed across the two time points.

Finally, separate paired sample *t*-tests was conducted to assess differences in backswing, forward swing and tempo across the two time points.

To assess for differences between the golfer's and coach's rating chi square analysis was conducted based on the yes or no feedback given post putt on green reading, start line, pace, intended aim point and execution accuracy. To assess for between group skill level differences (higher or lesser skill, based on median split average putts per round) independent sample *t*-tests were conducted to assess when the putt was successful if the golfer and coach's ratings match, i.e., after hitting a successful putt could the golfer identify whether they had correctly read the green, started online, hit the ball at the correct pace, hit their intended aim and executed the putt accurately. All data is presented as mean and 95% CI with the exception of the repeated measures ANOVA within and between for performance and this is presented as means and SE. Significance is accepted at $p < 0.05$ and when appropriate Bonferroni corrections were applied.

To assess whether there is a significant difference between the coach's rating and the golfer's rating in more detail, chi square analysis was conducted for the rating on each putt.

8.3 Results

8.3.1 Performance

Performance was lowest for the competitive putts and highest for the repetitive putt design (Figure 59). The main effect of time was not significant therefore no differences in performance were recorded between the summer and winter sessions [$F_{(1,10)} = 1.375$, $p = 0.268$]. There was a significant main effect for task design, therefore type of task influenced performance [$F_{(1.454,14.54)} = 97.55$, $p < 0.001$]. There was also a significant interaction for task design * time, [$F_{(1.422,14.22)} = 4.885$, $p = 0.036$]. Post hoc testing revealed there was a significant difference in performance between the competitive testing and the two repetitive putt task design in both winter (12ft indoor mean difference = 43.75, $p < 0.001$; 5ft outdoors, mean difference = 54.82% , $p < 0.001$) and summer (12ft indoor mean difference = 59.85, $p < 0.001$; 5ft outdoors, mean difference = 63.54% , $p < 0.001$). There was no difference in performance between the two repetitive conditions in winter (mean difference = 11.07, $p = 0.235$ or summer (mean difference = 3.961, $p = 0.767$).

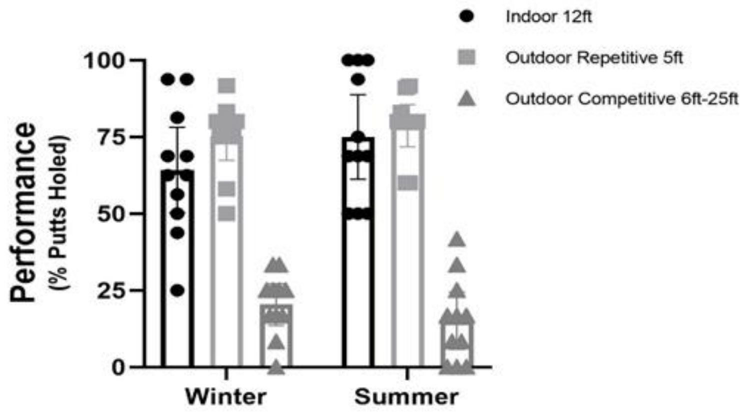

Figure 59. Comparison of performance on the different task designs, indoor repetitive 12ft, outdoor repetitive 5ft, outdoor competition at the Winter and Summer Testing sessions. Each dot represents an individual participant. Performance was lowest for the competitive task design. Performance was highest in the summer for the repetitive task designs but lower for the competitive task in comparison to the winter.

There was a significant difference in performance based on putt length (Figure 60), [$F_{(2, 30)} = 18.47$, $p < 0.001$], with most putts being holed at the distance of 7ft-15ft (15.15% ± 1.45), followed by short and long distance where the number of putts recorded was the same (11.36% ± 1.32 [short], ± 2.17 [long]). Surprisingly, performance was not higher at the shorter putts in comparison to the medium and longer putt distances. Post hoc testing, revealed there was a significant mean difference of 3.79% of putts holed ($p < 0.001$), between 6ft in comparison to 7-15ft, with more putts recorded as successfully holed at the medium distance. There was also a significant mean difference of 3.79% ($p = 0.01$) putts holed between 7-15ft and 16-25ft. There was not a significant difference in performance between 6ft and 16ft-25ft ($p > 0.05$), as the same number of putts were holed at these distances.

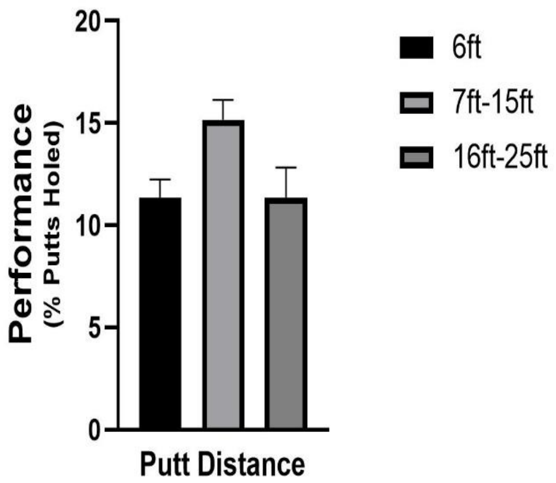

Figure 60. Putt success across the putt distances (short, medium and long) with 95% CI. Performance was highest at the medium putt distance.

There was a significant difference in performance based on slope (Figure 61), [$F_{(2, 30)}$ = 5.572, p = 0.008], with most putts (16.6% ± 1.5%) being holed at the moderate sloped condition (>1 % < 2%) , followed by limited slope (13.54% ± 7.11) and the severe slope (8.33% ± 7.21). Unexpectedly, performance was not higher in the limited slope compared to the other conditions that increased in slope. Post hoc testing, revealed there was a significant mean difference of 8.33% of putts holed (p < 0.001), between >1% < 2% in comparison to >2%, with more putts recorded as successfully holed at the lesser slope condition. There was not a significant difference between the other pairwise comparisons.

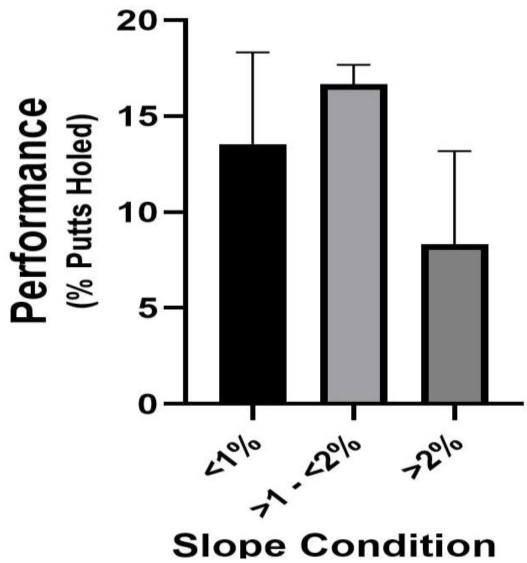

Figure 61. Number of putts scored at each putt type in the competitive putting task in-situ on a real green collapsed across both summer and winter conditions.

The higher skilled golfers scored more putts in the repetitive task (winter [80% ± 6.66] and summer [84.26% ± 5.57]) and in the summer competitive putts (23.61 ± 12.26) in comparison to lesser skilled (winter repetitive: 69.69 ± 14.51; summer repetitive: 72% ± 10.95% and summer competitive: 5% ± 7.45, respectively). In the winter competitive putts, the lesser skilled golfers scored more putts 25% ± 5.89 in comparison to the higher skilled 16.66% ± 11.78. The analysis (Figure 62) revealed there was not a main effect for putt type, [$F_{(1,9)}$ = 1.063, p = 0.329, η 2 = 0.106], however, there was an interaction for putt type * skill level, with putt type, [$F_{(1,9)}$ = 21.625, p = 0.001, η 2 = 0.706], meaning there were significant differences in performances based on the putt type as a function of skill level.

There was a main effect for time [$F_{(1,9)}$ = 381.774, p < 0.001, η 2 = 0.977], meaning performance level differed between winter and summer, although there was not an interaction for time * skill level, [$F_{(1,9)}$ = 1.056, p = 0.331, η 2 = 0.105] meaning these differences were not due to skill level. There was a significant interaction for putt type * time, [$F_{(1,9)}$ = 5.109, p = 0.05, η 2 = 0.362], meaning performance varied across the tasks across the two time points. Lastly, there was a significant interaction for putt type * time * skill level, [$F_{(1,9)}$ = 8.260, p = 0.018, η 2 = 0.479]. Overall, the higher skilled golfers performed better in comparison to the lesser skilled golfers and their performance improved from winter to summer in both tasks. However, the lesser skilled golfers' performance declined in the summer in comparison to winter on the competitive task when the pace of the green increased. Interestingly, the decrease in performance was not seen in the repetitive putt task.

Post hoc paired sample *t*-test found there was a significant differences in performance (Figure 62) based on putt type in winter (repetitive task: 75.27% ± 11.66; competitive task: 20.45% ± 10.11, $t(10)$ = 11.57, p < 0.001) and summer (repetitive task: 78.69% ± 10.22; competitive task: 15.15% ± 13.85, [$t_{(10)}$ = 18.35, p < 0.001]. A post hoc independent sample *t*-test found there was a significant difference in performance for the higher skilled group compared to the lesser skilled group in the summer competitive task, ($t_{(8.36)}$ = 3.094, p = 0.014). There were no differences in the other comparisons, i.e., winter competitive performance, ($t_{(7.59)}$ = 1.477, p = 0.169), winter repetitive performance, ($t_{(5.39)}$ = 1.51, p = 0.195) and repetitive summer, , ($t_{(5.7)}$ = 2.27, p = 0.066). Taken together these findings suggest expertise differences, can only truly be assessed using a representative task *in-situ*, on a surface that is comparable to what highly skilled golfers compete on.

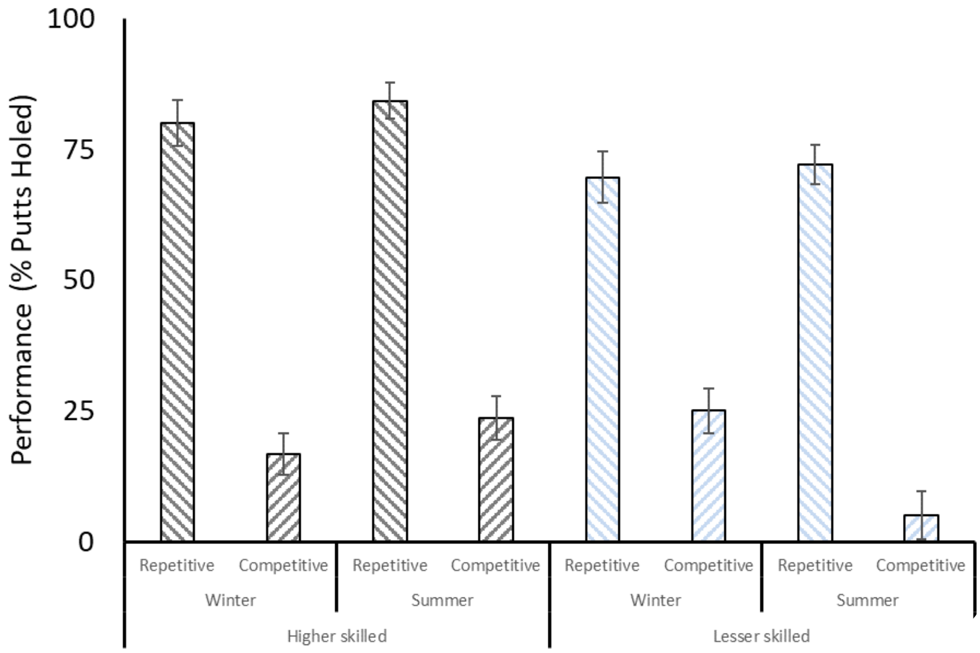

Figure 62. Differences in performance based on skill level and putt type (SE). The left to right chevrons indicate performance on the competitive task and the right to left chevrons represent performance on the repetitive putt task. Higher skilled golfers are represented by the dark grey bars and lesser skilled golfers are represented by the light grey bars. The greatest difference in performance as a function of skill level can be seen at the competitive summer task.

8.3.2 Kinematics

The higher skilled golfers had higher face at aim consistency (winter [74.33% ± 20.15] and summer [78.83% ± 11.16]) and impact spot consistency (winter [84.83% ± 13.27] and summer [81.50% ± 10.44]) in comparison to less skilled golfers face at aim consistency (winter [65.60% ± 29.50] and summer [51.20% ± 35.]) and impact spot consistency (winter [65.80% ± 25.05] and summer [58.20% ± 29.32]). However, the analysis, revealed there were no interactions or main effects ($p > 0.05$), meaning the differences were not significant and it could be concluded there were no differences in stroke kinematics based on skill level or across the two different time points.

To assess whether there were any kinematic changes between the winter and summer, the variables of ball speed, roll speed and club speed were examined. Additionally, specific stroke timings such as forwardswing, backward swing and tempo were assessed. Results revealed the ball, club and roll speed was significantly increased (Figure 63) in the summer in comparison to the winter (Table 12). However, there were no change in the stroke characteristics of backward swing, forwardswing and the tempo (Table 12). Taken together the findings suggest if golf putting is being practiced in winter, the coach and golfer will need to be aware that the ball will be behaving differently to how it will behave in the summer.

Table 12. Exploring the impact of timing (winter and summer) on kinematic variables.

Variable	Mean of Winter	Mean of Summer	Difference	SE of difference	t ratio	df	Significant?	Adjusted P Value
Ball Speed (mph)	7.08	8.814	-1.733	0.192	9.053	12	Yes	< 0.001
Roll Speed (mph)	4.928	5.878	-0.949	0.124	7.647	12	Yes	< 0.001
Club Speed (mph)	4.169	5.338	-1.170	0.136	8.576	12	Yes	< 0.001
Backswing Time (s)	0.7087	0.6884	0.020	0.107	0.1908	12	No	>0.999
Forwardswing Time (s)	0.3119	0.2926	0.019	0.037	0.5199	12	No	>0.999
Tempo	2.259	2.356	-0.098	0.173	0.564	12	No	>0.999

The data was average across the winter and summer testing sessions, (averaging across a range of putt distances and types) so to explore the range of minimum and maximum speed the data is presented in the Figure 63.

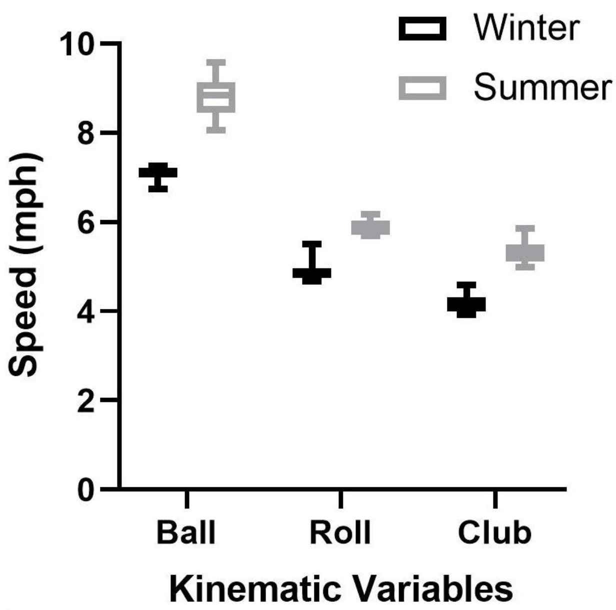

Figure 63. Changes in ball, roll, club speed (mph) based on the time (winter and summer).

8.3.3 Golfer and Coach rating on a putt by putt level

The golfers were more able to judge whether they had hit the putt at the correct pace (Table 14) and hit their intended aim point (Table 16). The golfers were also able to evaluate whether they had executed the putt in line with their read as they only differed from the coach's rating 16% of the time (Table 17). In contrast, the golfers seemed less able to correctly identify whether or not they had accurately read the green (differed in their ratings in comparison to the coach 54% of the time, Table 13) and started the putt on line (differed from the coach's rating 29% of the time, Table 15).

Table 13. Significant differences in judging green reading accuracy between the golfer and coach based on Chi Square analysis. The golfer and coach were significantly different in their ratings over 54% of the time.

Putt Type		Golfer		Coach		*DF*	*Chi Square*	*Sig*	
		Accurate	*Inaccurate*	*Accurate*	*Inaccurate*				
Winter 2	15ft <1% RL	8	3	3	8	1	4.545	0.033	Yes
Winter 4	20ft <1% RL	9	2	4	7	1	4.701	0.030	Yes
Winter 5	6ft >1%<2% LR	9	2	4	7	1	4.701	0.030	Yes
Winter 6	9ft >1%<2% RL	10	1	3	8	1	9.214	0.002	Yes
Winter 7	12ft >1%<2% RL	11	0	2	9	1	15.231	<0.0 01	Yes
Winter 8	18ft >1%<2% RL	8	3	2	9	1	6.600	0.010	Yes
Winter 9	6ft >2% RL	8	3	1	10	1	9.214	0.002	Yes
Winter 10	9ft >2% RL	9	2	1	10	1	11.733	0.001	Yes
Winter 11	12ft>2% LR	9	2	2	9	1	8.909	0.003	Yes
Winter 12	18ft>2% LR	8	3	3	8	1	4.545	0.033	Yes
Summer 8	18ft >1%<2% RL	10	1	5	6	1	5.38	0.022	Yes
Summer 11	12ft>2% LR	10	1	2	9	1	11.733	0.001	Yes
Summer 12	18ft>2% LR	10	1	3	8	1	9.214	0.002	Yes

Table 14. Significant differences in judging pace accuracy between the golfer and the coach based on Chi Square analysis. The golfer and coach had significantly different

Putt Type		Golfer		Coach		*DF*	*Chi Square*	*Sig*	
		Accurate	*Inaccurate*	*Accurate*	*Inaccurate*				
Winter 11	12ft>2% LR	7	4	2	9	1	4.701	0.030	Yes

Table 15. Significant differences in judging start line accuracy between the golfer and coach based on Chi Square analysis. The golfer and coach were significantly different in their ratings over 29% of the time.

Putt Type		Golfer		Coach		*DF*	*Chi Square*	*Sig*	
		Accurate	*Inaccurate*	*Accurate*	*Inaccurate*				
Winter 1	9ft <1% RL	7	4	2	9	1	4.701	0.030	Yes
Winter 3	18ft <1% LR	8	3	3	8	1	4.545	0.033	Yes
Winter 8	18ft >1%<2% RL	7	4	1	10	1	7.071	0.008	Yes
Summer 1	9ft <1% RL	7	4	2	9	1	4.701	0.030	Yes
Summer 2	15ft <1% RL	8	3	0	11	1	12.571	<0.001	Yes
Summer 5	6ft >1%<2% LR	10	1	4	7	1	7.071	0.008	Yes
Summer 10	9ft >2% RL	8	3	2	9	1	6.600	0.010	Yes

Table 16. Significant differences in judging aim point between the golfer and the coach based on Chi Square analysis. The golfer and coach had significantly different ratings 4% of the time.

Putt Type		Golfer		Coach		*DF*	*Chi Square*	*Sig*	
		Accurate	*Inaccurate*	*Accurate*	*Inaccurate*				
Winter 8	18ft >1%<2% RL	6	5	0	11	1	8.250	0.004	Yes

Table 17.Significant differences in judging execution based on Chi Square analysis. The golfer and coach had significantly different ratings 16% of the time.

Putt Type		Golfer		Coach		*DF*	*Chi Square*	*Sig*	
		Accurate	*Inaccurate*	*Accurate*	*Inaccurate*				
Winter 2	15ft <1% RL	8	3	3	8	1	4.545	0.033	Yes
Winter 8	18ft >1%<2% RL	7	4	0	11	1	10.267	0.001	Yes
Winter 9	6ft >2% RL	7	4	2	9	1	4.701	0.030	Yes
Summer 6	9ft >1%<2% RL	9	2	3	8	1	6.600	0.010	Yes

Start line accuracy based on skill level

An independent sample *t*-test was conducted to see if there was a difference in start line accuracy (i.e., accuracy was defined as when the golfer's rating matched the coach rating and it was judged to be correct) due to differences in skill level (median split based on average putts per round). Higher skilled golfers correctly matched the coach's rating more often (32.63% ± 15.23) in comparison to lesser skilled golfers (24.16% ± 12.63), however, there was not a difference between the groups ($t_{(8.99)} = 1.008$, $p = 0.340$), meaning there were no skill based differences in a golfer's ability to correctly assess whether they started the putt online.

Pace accuracy based on skill level

An independent sample *t*-test was conducted to see if there was a difference in pace accuracy (i.e., accuracy was defined as when the golfer's rating matched the coach rating and it was judged to be correct) due to differences in skill level (median split based on average putts per round). Higher skilled golfers correctly matched the coach's rating more often (31.94% ± 10.75) in comparison to lesser skilled golfers (29.16% ± 4.16), however, there was not a difference between the groups ($t_{(8.99)} = 0.582$, $p = 0.579$), meaning there were no skill based differences in a golfer's ability to correctly assess whether they hit the putt at the correct pace.

Aim Point accuracy based on skill level

An independent sample *t*-test was conducted to see if there was a difference in aim point accuracy (i.e., accuracy was defined as when the golfer's rating matched the coach rating and it was judged to be correct) due to differences in skill level (median split based on average putts per round). Higher skilled golfers correctly matched the coach's rating more often (25% ± 8.74) in comparison to lesser skilled golfers (15.83% ± 12.28), however, there was not a difference between the groups ($t_{(7.07)} = 1.399$, $p = 0.204$), meaning there was no skill based differences in a golfer's ability to correctly evaluate whether they had hit their intended aim point.

Execution accuracy based on skill level

An independent sample *t*-test was conducted to see if there was a difference in execution accuracy (i.e., accuracy was defined as when the golfer's rating matched the coach rating and it was judged to be correct) due to differences in skill level (median split based on average putts per round). Higher skilled golfers correctly matched the coach's rating more often (18.75% ± 5.74) in comparison to lesser skilled golfers (10% ± 6.31). Furthermore, the analysis revealed there was a significant difference between the groups, meaning higher skilled golfers were more accurate at judging their execution in comparison to lesser skilled golfers, $t_{(8.26)} = 2.383$, $p = 0.043$.

8.4 Discussion

The current study was designed to explore the underpinning perceptual-cognitive processes associated with successful putting performances when completing a representative golf task. Consequently, 11 golfers attended testing at two time points (winter and summer). At these testing sessions, performance, kinematic measures, alongside coach feedback were captured to explore the impact of the task and the environment on performance and stroke. Furthermore, this data was used to help form the basis of the coach's assessment on whether or not the golfer had accurately rated their green read, execution and associated putt characteristics, such as start line, aim point and pace during the representative task. In addition, a final aim of this study was to compare performance on a representative task (competition putts) in comparison to two non-representative tasks (repetitive; 5ft putt outdoors and 12ft putt indoors) completed on the same day.

Findings revealed performance was much lower on the representative task (competitive putts), ranging from 0% to a maximum of 25% success, in comparison to the non-representative task (repetitive putts) were performance ranged from 60% to 100%. Moreover, there were no differences in performance on the two repetitive putt tasks, despite the change in putt distance from 5ft to 12ft and one task being completed indoors and one outdoors. These findings do reinforce the importance of using a representative task design, to ensure the task has 'action functionality' and 'action fidelity' (for definitions please see Chapter 1) so the task adequately replicates the performance environment and the specific settings the findings are intended to be applied in (Pinder et al., 2011). Alongside, the performance measure, it was also found the golfers struggled to read the green correctly and consistently evaluate whether they had read the green accurately. Taken together, our findings suggest when the green reading component of the putt is high, performance decreases in comparison to when the green reading requirement is low. Our findings are supported by Karlsen and Nilsson, (2009) who found for highly skilled golfers, green reading accounted for 60% of the variance in putting performance. Therefore, it is critical, research continues to explore links between green reading, perceptual-cognitive expertise, and performance in order to make tentative steps towards providing evidence based recommendations to coaches and golfers.

To understand how the golfer develops skilled perception and action, it is important to explore how the golfer is creating functional linkages between perceptual information and movement-control parameters (Farrow & Abernethy, 2003). Findings suggest the golfers were less accurate than the coach in their ratings evaluating set up to their read, and execution of the putt based on their chosen read. Additionally, our findings suggest the golfers did not always set up correctly to the read they chose and that there were inaccuracies in their alignment. Thus, highlighting their feedback and evaluation of the putt, post putt was not reliable, and this could influence the ability to create functional linkages between perceptual information and movement control (Stone et al., 2013). Furthermore, we also found in some instances golfers changed the read whilst over the ball, (i.e., in the final seconds preceding the start of the motor action) and set up to a different read from their original intended/marked aim point. This presented an interesting observation: that the golfers changed the read of the putt whilst over the ball, meaning information gathered in the first part of the routine was ignored, based on information they had gathered over the ball. This means it is important to explore which sources of information golfers are using from the environment to make their decisions in more detail.

These findings also are consistent with the utilisation of affordance (opportunities for action invited by objects, and features in the surface, *cf*. Gibson, 1979), where the golfer in the performance environment is continuously perceiving new information and choosing whether or not to act. Notably, for functional perception-action coupling to occur the individual must be able to identify the correct information in the environment and be able to scale their action capabilities to this information (Fajen, 2007; Jacobs & Michaels, 2007). To be able to train functional perception-action coupling and to develop awareness of the sources that an individual is using, it is important to understand how an individual is navigating through an ever-changing environment (Sherman & Craig, 2002). The self-ratings offer one way to gain information about the golfer's cognitive processes and how they are interacting with the environment. For example, golfers were able to accurately evaluate whether they had hit the putt at the correct pace and had hit their intended aim. Arguably these are sources of feedback the golfer can more readily see and access within the green environment. This is supported by research that has found that skill transfer is effective when an athlete has had prior experience of the environment, but also has the capacity to transfer perceptions, cognitions and actions between performance environments (Seifert et al., 2016b).

Similarly, our findings highlighted an expertise difference in the ability to read the green, with higher skilled golfers more able to accurately identify the green read and execute the putt correctly compared to lesser skilled golfers in the summer competition putt condition. This finding is consistent with research suggesting experts are better at green reading then less skilled amateurs (Pelz, 1994; Campbell & Moran, 2014). In contrast, these differences were not present during the winter testing session and we found the increase in performance was not due to superior stroke kinematics, as no expertise based differences in stroke kinematics at either time point (summer/winter) were found. Taken together, these findings suggest that expertise difference could only be revealed when the conditions represented settings which enabled the higher skilled golfers to demonstrate their expertise. For example, the pace (ball and roll speed) of the summer green was much quicker than the pace of the winter green and more comparable to the pace on the Tour or at elite amateur golf tournaments. Critically, measuring the whole putting routine (pre and post) enabling the continuous coupling of informational constraints and actions during testing sessions (Stone et al., 2018) is important to ensure future testing can continue to develop knowledge on how a golfer develops perceptual-cognitive expertise.

Our kinematic findings on the stroke were consistent with evidence that suggests the ideal ratio is considered to be 2:1 i.e., backswing phase being twice as long as the forwardswing (Grober, 2009; Kooyman et al., 2013), regardless of the target distance of the putt (Grober, 2011). However, when examining putter variability with 10 ‘highly skilled’ golfers (handicap M = 10.82 – no other measures of putting expertise reported) on an artificial indoor carpet green, Dias *et al*. (2014) found participants altered their backswing, club speed and acceleration at the moment of impact with the ball to adjust to the task constraints. To examine different task constraints, Dias *et al.* (2014) asked participants to complete two conditions straight and slope. The first condition was 90 straight putts (30 putts at distances of 2, 3 and 4 meters) and the second condition was 90 sloped putts (same distances as condition 1). The most notable finding was the level of variation in the way the participants responded to the task constraints and manipulated the putter, suggesting that there are main different ways to achieve the task goal. This is supported by research by Mendes *et al*. (2012) that found when examining putter variability in a similar task to Dias *et al*. (2014) with 10 male right handed adult golfers (10.82 ± 5.4 handicap) that there was a high level of intra and inter-variability and concluded that each participant had a unique' signature putting' movement. Similarly, Couceiro *et al.* (2013) also found golfers had a unique identifiable putting signature when applying pattern detection analysis. These findings are in accordance, with the concept of redundancy (Ranganathan & Newell, 2013). Redundancy has been defined as "*multiple ways to execute a movement to achieve the same task goal*" (Ranganathan & Newell, 2013, p.65). Currently, there is paucity of research exploring putter variability linked to the environment in golf putting (Robertson & Farrow, 2017) and it is recommended that future research, should continue to explore this interaction and how the golfers can alter their stroke kinematics in order to putt successfully.

When considering the applied implications of our findings, we propose that an intervention centred around pace and aim point would be useful for retention as the golfer is able to reliable monitor and evaluate these sources of information. Although, caution is required as our findings suggest that to improve green reading accuracy and evaluation around start line and execution an educational intervention is required. To help promote the transfer it is critical that feedback sources that are available *in-situ*, and participants can evaluate themselves without technology.

The study design enabled the researcher to develop further understanding on perceptual cognitive expertise. For example, by testing at different time points in the year in varying conditions this highlighted the importance of understanding how a golfer is interacting with their environment and task. Secondly, by using the competitive putts combined with the ratings pre and post putt, this enabled perceptual-cognitive expertise to be conceptualised using the whole putting routine, and this allowed the researcher to capture the continuous nature of perception action coupling. Lastly, by comparing and contrasting representative tasks with non-representative task on the same day, this allowed for a performance comparison to be made, providing information on how the task design influences performance.

Crucially, a limitation of this study, was that we were unable to collect information on visual strategies and specific information about where a golfer was looking during their putt routine using eye trackers. The eye trackers could not be reliably used outside in the winter due to problems with low light and variable light conditions in the summer. Further development is needed in this area and due to lack of technology advancement, it is suggested that a change from outdoors to an indoor putting environment is made for the next study.

8.5 Conclusion

This study found green reading does impact performance. Participants could not always accurately read the green and a participant may not always set up to the putt accurately. At this stage further research is required to determine how participants could be taught to consistently read the green and set up to their putt. An intervention study needs to be developed to explore if participants can be taught green reading skills to significantly improve performance.

Chapter 9: Study 4 – Moving towards the development of a Perceptual-Cognitive intervention to improve performance

9.1 Introduction

Green reading ability has been found to be a critical factor in golf putting success (Karlsen & Nilsson, 2008). In their study, Karlsen and Nilsson (2008), asked 43 highly skilled golfers (handicap = 2.8) to complete 40 putts, ranging from 2.2 to 19.3m in distance (uphill, downhill with right and left breaks) on a two-tiered grass to test the perceptual aspects of green reading. Karlsen and Nilsson's (2008) findings revealed green reading ability accounts for 60% of performance compared to technique at 34% and green inconsistencies at 6%. Consistent with these findings, research has highlighted the need to recognise that "*…successful putting entails more than proficient movement control, but requires… skillful perception*" (van Lier et al., 2011, p. 349). An example, of skillful perception is speed control (Pelz, 2000). To select the correct speed of putt, the golfer must first judge the pace, through taking in information about the surface and contours of the green through their green reading processes (Pelz, 2000). Then the golfer, must be able to use this information to manipulate the ball speed through their stroke by controlling the putter head with a controlled face aim (Karlsen et al., 2008). How a golfer develops skillful perception is a topic that is emerging and of considerable relevance to the applied domain because putting ability is considered to be the leading factor influencing determinant of earnings (Alexander & Kern, 2005).

To enable successful golf putting, the golfer must select the appropriate strategy (associated starting line, pace, aim point) and then execute the putt to ensure the ball remains on the intended path at the correct pace (Kenyon, 2008). The findings from Study 3b (Chapter 8), highlighted when golfers were engaging in putting task, there is a need for them to adapt, perceive, understand, and act within a changing and complex environment. The findings revealed golfers of varying skill level (ranging from -25 handicap to Tour Professionals) were not able to reliably read the green accurately, then set up to their chosen read and evaluate their action. These findings were unexpected, particularly in the case of the highly skilled participants, albeit they are not surprising given the lack of evidence-based coaching on green reading (Carey et al., 2017). Clearly, being able to evaluate these factors accurately is important to maintain successful putting, however what is not clear is whether the golfers can accurately identify the perceptual sources in the environment to judge their appraisal on for these factors. In contrast, in Study 3b, (Chapter 8) golfers were able to evaluate their pace and whether they could hit their intended aim, suggesting that golfers can use perceptual sources in the environment. Taken together, these findings highlight how complex developing and measuring skillful perception is. However, they do offer promise that skillful perception can be learnt through teaching golfers how to use perceptual sources in the environment.

In accordance with the principles of an ecological dynamics perspective, exploring an individual's experience in the environment and how their experience influences how they process the world around them and their chosen actions has been a central focal point of much sporting research (Araújo et al., 2006; Davids & Araújo, 2016; Davids et al., 2012). From an ecological dynamics perspective, the environmental properties can directly inform an individual about what he/she can and cannot do in a performance environment (Gibson, 1979). The concept of affordances (*cf*. Gibson, 1979) has been developed to explain how the environment (surfaces, texture and objects) provide the individual with opportunities to act in a continuous cycle (Davids et al., 2013). In the case of affordances, it is assumed that the environment is perceived in terms of what actions can be achieved within the performance environment and subsequent action is not dependant on the individual's expectations (Richardson *et al.* 2008). Thus, an affordance-based approach has been found to be an effective way of improving behaviour through using the environment to maximise the potential of the individual (Kaaronen, 2017).

The premise of the perceptual-cognitive intervention in this study was designed based on an affordance-based approach. For example, the perceptual information within the intervention has been designed to give the participant a chance to 'perceive affordances' and to provide the participants with information on functional properties of the environment and the ways that they can act within the performance environment to achieve their task goal. More specifically, the intervention is based on the findings of Seifert *et al.* (2017) study which found skilled climbers used the preview time to become aware of functional properties of the environment and to become perceptually attuned to affordances. Therefore, the intervention has been designed to enable the golfers time to preview the holes (without hitting the putt) and to interact with perceptual information in the environment to attune to affordances in the environment.

Critical to understanding skilled perception and action, is employing a research design which allow participants to act in response to perceptual information in the environment, as part of the perception action coupling process inherent in the applied environment (Brunswik, 1956; Gibson, 1979; Warren, 2006). Therefore, in order to accurately explore perceptual-cognitive expertise, a representative environment is essential (Stone et al., 2017) as an unrepresentative environment will cause inaccuracies in visual display, potentially altering selection of relevant and irrelevant environmental information and subsequent integration with existing knowledge (Stone *et al.* 2013). In addition, a non-representative task could potentially change the task or alter the task goal which could force the athlete to use unfamiliar ways to complete the task, resulting in the task no longer measuring the underlying processes in the interaction and how this is mediated by expertise (Williams & Ericsson, 2005; Dicks et al., 2009).

Therefore, the aim of this study, is to explore if developing a perceptual-cognitive intervention underpinned by ecological dynamics perspective can help to improve golf putting performance and green reading. Furthermore, it is of interest to explore if a perceptual-cognitive intervention can help a golfer to appraise their putt accurately. We hypothesise, performance and the ability to accurately evaluate putt characteristics will improve in line with increased perceptual-cognitive skill. Additionally, we aim to capture eye tracking and EEG data as an avenue to gain further understanding on the basic mechanisms that underlie successful putting and to assess whether the intervention changes leads to any changes in gaze strategy or neural activity. Lastly, we are interested in exploring whether perceptual skills (non-motor) are related to the performance.

9.2 Methodology

9.2.1 Participants

Participants were nine experienced golfers (eight males and one female, aged between 19 years and 28 years), including five amateurs (handicaps ranging from 0 to +5) and five professionals. All were right handed, right eye dominant, and had normal or corrected-to-normal vision. Participants' average putts per round were 28-31 putts and average greens in regulation was 68%.

9.2.2 Procedure

Ethical approval was granted by the University of Stirling Psychology Ethics Committee. All procedures were in accordance with the Declaration of Helsinki ethical principles for collecting research with human participants The lead researcher contacted the Performance Director from the Scottish Golf Union for permission to speak to players matching the eligiblity criteria, to determine interest in participating in the study. The lead researcher then met interested players to explain the study requirements and related information. Following this meeting, players were asked to confirm involvement in the study by sending the lead researcher a signed copy of the informed consent sheet and demographic information. Players were made aware that participation was not a requirement, that it was voluntary without obligation and that participation had no influence on training and selection. There was no coercion to participate from either coaches or the lead researcher: all participation was voluntary and consent for participation was obtained prior to participants starting testing.

Participants attended the testing sessions individually and used their own putter (fitted by a golf professional prior to the study, to ensure consistency for all participants) and Srixon AD333 Tour golf balls were provided, consistent with other studies in this thesis. Participants were given an opportunity to ask questions prior to commencing the experiment and asked not to discuss the experiment following the session. Testing was 3.5 hours in duration (see Figure 64) whereby participants firstly completed the Motor Free Visual Perception Questionnaire, then completed 4 x 10 putts (straight and sloped 8ft-15ft) pre intervention putts. Participants then followed a 15-minute perceptual cognitive expertise green reading intervention and completed 4 x 10 putts (straight and sloped 8ft-15ft). Putts were different pre and post intervention, but were matched for difficulty level. Slopes included both L-R and R-L and ranged from 0-1% slope, 1-2% >2% sloped. All putt distances and slopes were counterbalanced. Prior to putting, participants marked their aim point and rated their confidence levels pre putt (the same as Study 3b). Following the putt, consistent with Study 3.2, participants and their coach independently assessed whether the green had been accurately read, started online; hit the putt at the correct pace; hit intended aim point and had executed putt correctly. Ratings were Yes or No, and the coach could use the kinematic feedback provided by Trackman to support assessment.

Figure 64. Schematic of Methodology for Study 4.

9.2.3 Intervention

The intervention has been designed specifically for this study, based on previous perceptual-cognitive interventions (Seifert et al. 2017) and aided participants to identify relevant cues in the environment a) giving participants cues from a video of an expert hitting the putt and b) information about the perceptual cues in the environment through showing how the intended path and aim point changes depending on what pace to hit the ball at minimum and maximal pace (see Figure 65). To help reinforce perceptual cues a video of the expert ball rolling the same putt was also provided (see Figure 66). After participants had watched the two videos, they were given five minutes to help understand the link between perception and action through the exploration of the surface/environment using a ball roller to 'roll' their putt towards the hole.

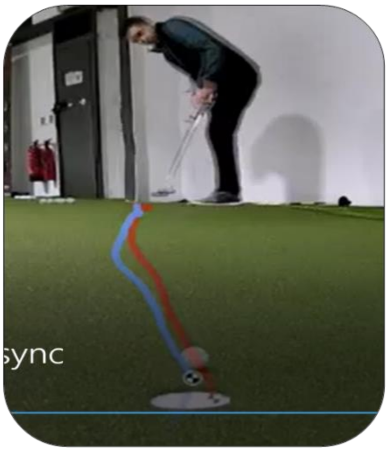

Figure 65.Example footage showing minimum (red line) and maximum (blue line) lines for a 15ft >2% Sloped Downhill Putt.

Figure 66. Example footage showing the expert using a ball roller for a 15ft >2% Sloped Uphill putt.

Prior to completing putts, an ASL mobile eye tracker (XG Mobile Eye Tracker, Applied Science Laboratories, Waltham, MA) and EEG equipment (eego™**sports,** ANT-Neuro, Enschede, The Netherlands) were fitted to the participant via the lead researcher, consistent with previous research in this thesis. The eye tracker calibration was consistent with Study 1, 2a, 2b and recalibration was conducted at every new putt location and if the glasses had been moved. The same EEGO sport mobile EEG system with 32 Ag/AgCl electrodes, trigger and data processing settings were consistent with those outlined in Study 2b.

9.2.4 Measures

9.2.4.1 Performance

Performance was assessed through the number of successful putts. All putts were inside the 'winning zone' (8ft-15ft) so error was not measured as participants of this skill level were aiming to hole these putts. It is of interest to explore if anything differentiated the successful shots from unsuccessful putts.

9.2.4.2 Motor-Free Visual Perception test (MVPT-4)

The MVPT-4 is the only non-motor visual perceptual assessment which can be used throughout the lifespan and consists of 45 items that assess visual discrimination, spatial relationships, visual memory, figure-ground and visual closure. Each item is comprised of black-and-white line drawings and designs, whereby participants are asked to select the correct answer choice from four options presented in an easy to record multiple-choice format. The MVPT-4 has sound reliability and validity and each score can be aged normed (Colarusso & Hammill, 2015). Raw scores are converted to standardised scores which are presented as means and standard deviations, with a percentile rank. Based on the standardised scores participants were placed into three groups, low, medium, and high.

9.2.4.3 Visual Search Behaviours

Visual search behaviours were captured in accordance to Study 2a.

Swing Kinematics:

Kinematic variables were captured by TrackMan4 (Denmark). Consistent with Study 3b, the aim point was calibrated during the set-up process for each putt and numerical information on ball speed, roll speed, club speed, tempo, forwardswing and backswing was collated.

EEG Data processing

The data processing methods were the same as those outlined in Study 2b.

9.2.5 Statistical Analysis

Performance was measured by a within repeated measures analysis of variance (ANOVA) to explore whether intervention, putt type or trial number influenced putting success. To explore whether there was a difference in performance based on visual perceptual skill a within participants repeated measures ANOVA was conducted to determine any differences between the Intervention (2), * Putt Type (4) * Trial Number (10).

To explore kinematics change pre and post intervention, separate paired sample *t*-tests were used to compare differences in ball roll, ball speed and club speed across the two time points. Finally, separate paired sample *t*-tests was conducted to assess differences in backswing, forward swing and tempo across the two time points.

To explore whether non motor visual perception influenced performance, a within between repeated measures ANOVA; with the within factor time (2; performance pre and performance post intervention) and the between factors (3; low, medium, high based on the standardised scores on the Motor-Free Visual Perception test) was conducted.

To explore whether visual strategy changed post intervention in comparison to pre intervention, a series a paired sample *t*-tests were conducted for final viewing time of the ball, QE duration. To explore whether the coach and participants' rating of the green reading accuracy, start line, pace, aim point and execution were different for each putt (pre and post intervention) Chi square analysis was conducted. Means and 95% CI are presented, and significance level was accepted at $p < 0.05$.

9.3 Results

9.3.1 Performance

Performance was higher post intervention in comparison to pre intervention (Figure 67), including differences in the outcome of the first putt, with 2% success pre intervention and 49% success post intervention. The main effect for Intervention was significant [$F_{(1,8)}$ = 15.56, p=0.01, η^2 = 0.756] with more putts being successfully holed post intervention. The main effect for Putt Number was significant, [$F_{(3.35,26.85)}$ = 3.796, p = 0.01, η2 = 0.432], with more putts being holed as the trial number increased. The main effect for Putt Type was not significant, [$F_{(2.39,\ 19.17)}$ = .492, p=0.693, η^2 = 0.97] meaning performance did not vary across the four putt types regardless of the change in task difficulty. A significant interaction was found for Intervention * Putt Number, [$F_{(2.93,\ 23.44)}$ = 2.456, p = 0.023, η^2 = .329], and this may be driven by the change in success in trial 1 post the intervention in comparison to pre the intervention (Figure 67). There was no interaction for Intervention*Putt Type [$F_{(1.92,\ 15.38)}$ = 0.804, p = 0.511, η^2 =.139] and for Putt Type * Putt Number, [$F_{(.33,\ 26.64)}$ = 1.49, p=0.79, η^2 = .230]. There was no three-way interaction between Intervention * Putt Type * Putt Number, [$F_{(12.44,\ 30.63)}$ = 7.83, p=0.796, η^2 = .135].

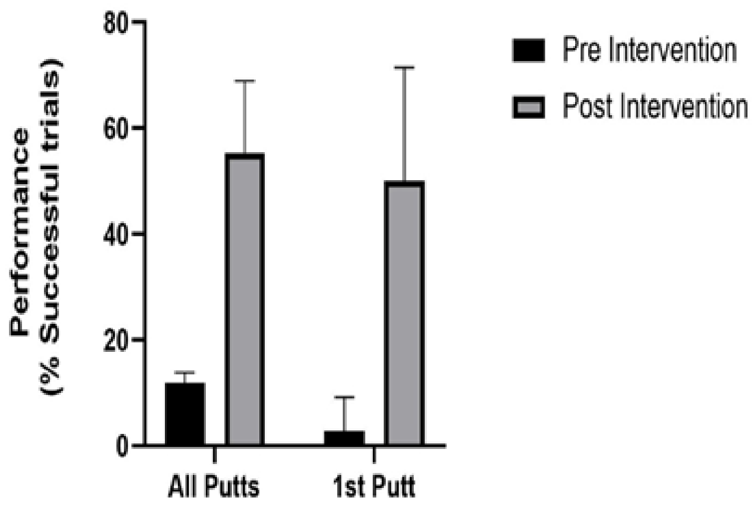

Figure 67. Mean performance (95% CI) Pre and Post Green Reading Intervention.

9.3.2 Kinematic variables

To assess whether there were any kinematic changes post the intervention, the variables of ball speed, roll speed and club speed were examined. Additionally, specific stroke timings such as forwardswing, backward swing and tempo were assessed. Results revealed that there was a significant decrease in ball speed, roll speed and club speed post intervention in comparison to pre intervention (Table 18) suggesting the intervention influenced the participants ability to control the speed of the putt. However, there were no change in the forwardswing, backswing and tempo, so this implies that the change to the club speed was during contact (Table 18).

Table 18. Examining changes in kinematic variables pre and post the intervention.

Variable	Mean of Pre	Mean of Post	Difference	SE of difference	t ratio	df	Significant	Adjusted P Value
Ball Speed (mph)	6.001	5.305	0.696	0.167	4.173	16	Yes	0.004
Roll Speed (mph)	4.152	3.716	0.436	0.108	4.022	16	Yes	0.006
Club Speed (mph)	3.575	3.234	0.341	0.097	3.531	16	Yes	0.017
Backswing Time (s)	0.7132	0.7069	0.006	0.064	0.098	16	No	>0.99
Forwardswing Time (s)	0.3296	0.3337	-0.004	0.016	0.258	16	No	>0.99
Tempo	2.163	2.114	0.049	0.141	0.345	16	No	>0.99

To explore the change in ball speed, roll speed and club speed on an individual level, the data is presented in Figure 68. The decrease is speed was consistent for all participants.

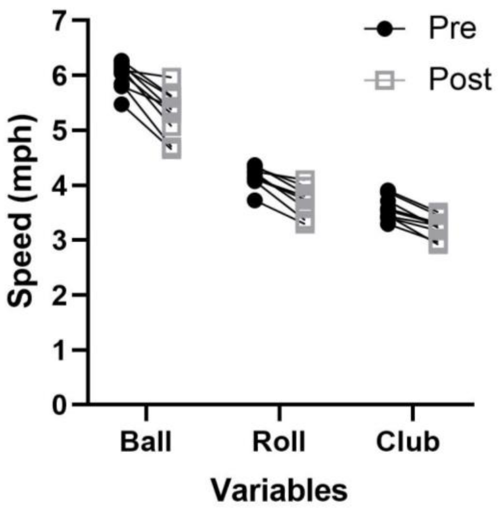

Figure 68. Exploring individual differences in change of ball, roll and club speed, pre and post the intervention.

9.3.3 Visual Perceptual Skills and Performance

Participant scores ranged from 2nd percentile to the 95th percentile on the NMVP, suggesting a wide range of visual perceptual skill from less than average to very high. The average score fell within the 60th percentile, just above the mean score found in research by (Anastasi & Urbina, 1997). The mean scores suggest visual perceptual skill is not related to performance pre-intervention (low: 32.5% ± 7.5; medium: 24.16% ± 5.2; high: 30% ± 4.33). Post-intervention, those participants who had higher visual skills performed better compared to those with lesser, but those with lower visual perceptual skills performed better than those with medium visual perceptual skills (low: 53.3% ± 3.81; medium: 45.83% ± 5.2; high: 69.16% ± 22.68). The analysis revealed there was a main effect for time (consistent with the performance above), however, the improvement in performance was not related to visual perceptual skills, as there was no interaction for time * visual perceptual skill ($F_{(2, 6)} = 1.68$, $p = 0.263$, $\eta^2 = .359$).

9.3.4 Visual Strategy and QE

Mean duration time for viewing time on the ball prior to QE and QE duration were similar pre and post intervention. The analysis revealed there was no difference in duration for the visual gaze characteristics pre and post intervention ($p > 0.05$), therefore the gaze strategies did not change because of the green reading intervention.

9.3.5 Participant and Coach Ratings

There were inconsistencies in a golfer's ability to accurately read a putt in comparison to the coach (Appendix 3). However, the participants were more able to evaluate their green reading and execution in line with the coach's appraisal following the intervention. The participants struggled to accurately evaluate start line even after the intervention. Participants were able to evaluate their pace and aim point in line with the coach's judgment of the situation.

Can a golfer accurately read the green?

The findings of the chi square analysis suggest the participants' ratings were more similar to the coaches rating post the intervention, with only one occurrence of significantly different ratings between the participant and coach post-intervention, in comparison to 14 occurrences pre-intervention (Appendix 3). These findings suggest the intervention did help the participants/golfers to accurately read the green.

Can a golfer start their putt on the correct start line?

Participants differed from the coach's rating for most of the trials, pre and post intervention (Appendix 3). The findings would suggest the participants are not able to evaluate their start line and further training is required. The intervention was not effective for helping a golfer to evaluate their start line, despite it being effective for the golfer to improve their ability to read the green. This finding would suggest that start line is independent to green reading and even though the golfer has read the green correctly this does not mean they can accurately set up to the putt.

Can a golfer accurately evaluate the pace?

The participants were similar to the coach in their ratings of whether or not they hit the putt at the correct pace, with only two occurrences pre-intervention and three occurrences post-intervention where their ratings were significantly different (Appendix 3). The findings suggest the participant can evaluate pace and the intervention did not improve or change their ability to do this.

Can a golfer accurately evaluate their intended aim point?

The intervention provided the participant with the intended aim point, however, surprisingly post the intervention there was not a difference in how many times the coach's and participants' ratings significantly differed from each other in comparison to pre-intervention (Appendix 3). Although, the times where the participants and coach differed was limited with only six instances out of a total 40 putts (pre and post intervention).

Can a golfer accurately evaluate their own execution?

The number of times that the participant and coach differed in their ratings was less post (2 occurrences) intervention in comparison to pre-intervention (8 occurrences), suggesting the intervention did improve the participant's ability to rate their execution (Appendix 3).

9.3.6 Is there a difference in neural activity pre and post intervention?

There were not enough clean trials based on Cohen (2016) recommendations to run an analysis on neural activity as a function of performance for each condition. The low trial number was confounded by the one session and small sample size. There was also an increase in signal noise within the sporting venue on some of the testing days meaning electrode impedance at each channel couldn't be maintained below 10 kΩ for every participant. Therefore, more trials and further exploration into the increased signal noise are needed in the future. This poses an interesting discussion point around the use of EEG for representative task design, especially as it is difficult to recruit a larger sample size. Further research would need to involve a great number of sessions to increase the trial number per participant.

9.4 Discussion

Nine highly skilled golfers completed a perceptual-cognitive intervention designed to improve performance. The intervention was designed to improve performance, by improving a participants’ ability to select and hit the appropriate putt through guiding the participants to the ‘right’ perceptual information in the environment/provide information to guide learning about affordances in the environment. It was also of interest to explore if the intervention changed cognitive processes underpinning putting and could be used to improve a participants’ ability to accurately appraise their putt. Furthermore, we were also keen to explore the interaction between the individual, task, and environment (Newell, 1986), specifically looking at whether the intervention changed a participant’s gaze strategy or selected kinematic variables. Lastly considering the individual, we examined if perceptual skills (non-motor) impacted on performance both pre and post intervention.

Findings revealed a practical perceptual-cognitive intervention can be taught to help enhance performance. Critically as well as improving overall performance, performance on the first trial at each putt position was improved i.e., when the putt was unique and unfamiliar to the participant, consistent with competitive golf. The intervention provided the participant with key perceptual information and the participants were able to use this knowledge to help hit an appropriate putt and to improve their feedback. In the intervention participants were given perceptual information on the pace (minimum/maximal pace and associated reads) and the aim point. The increase in performance, suggests the participants were able to use this information to inform their motor action. Crucially, the intervention did not prime the participant- in the intervention the participant learnt all the putts together (akin to preview time). Additionally, the putts in the post intervention testing condition were in a different order to how they were displayed during the intervention (preview), so this provides support that the participant (golfer) had the capacity to transfer perceptions, cognitions and actions (Seifert et al., 2016). However, the short time frame between conditions and the lack of transfer and retention test does limit the potency of these performance benefits.

Influencing the participants experience in the environment via the intervention did influence subsequent motor behaviour, consistent with the tenets of the Ecological Dynamics approach. An Ecological Dynamics approach postulates an individuals’ movement responses are shaped as a result of the continuous dynamic interaction between the individual, task and environment (Araújo, Davids, and Hristovski 2006). Gibson (1966) describes how the brain and body (sub)systems are involved in a process whereby the perceptual and action systems function in a highly integrated, interconnected and cyclical manner. Critically, in order to perceive information for action an individual needs to be able to 'tune' into this information, via the "*resonance mechanism*" (Teques, Araújo, Seifert, Del Campo, & Davids, 2017, p. 40). Without 'proper tuning' the individual does not resonate with the perceptual information. Therefore, it could be suggested based on the differences in post intervention performance scores and the increased ability to read the green, execute the putt at an appropriate pace (but no changes in start line) the intervention did help the participants to become more 'attuned to their environment'. Furthermore, post intervention participants were more able to evaluate these factors post putt demonstrating improvements in performance and most notably the ability to transfer learning. Therefore, to expand on these areas, we propose developing perceptual-cognitive expertise is not a passive skill. Consistent with Gibson (1979) belief that '*we must perceive in order to move but we must also move in order to perceive'* (p. 223). Taken together, these findings highlight that to develop understanding of green reading, it is important that putting surface (and variability) is the same as competitive putting on a golf course to be able to capture the complex interactions between the task and individual.

When exploring the interaction between the golfer, the task and the environment, research has suggested it is important to identify what parts of behaviour change, and which parts stay consistent (Seifert et al., 2016). Our findings reflect viewing time on the ball prior to QE or QE duration did not change irrespective of the intervention, suggesting the intervention did not change gaze behavior within the motor phase of the golf putt routine. Research has suggested QE duration is related to online control, so arguably QE duration was not expected to change following the intervention (Vine et al., 2013; Causer et al., 2017). Milner and Goodale (2008) have proposed a Two Visual System model that separates 'Vision for Perception' and 'Vision for Action'. The first system takes place in the ventral steam, the individual selects appropriate cues and action, based on their goals. In the case of post intervention this information was provided to the participant. The second system takes part in the dorsal stream, which is responsible for the online control of movements and for mapping the visual information directly to the action in the 'here and now'. These findings suggest perceptual-cognitive expertise is multi-faceted is more complex that just measuring QE duration alone.

At this stage, it is not possible to attain whether participants looked at different sources of information in the environment, pre and post the intervention when putting due to limitations in the eye tracker equipment. Eye trackers only pick up central vision and the fovea, the part of the eye that captures central vision, does not pick up all the information in the visual field (Holmqvist & Andersson, 2017). When recreating the visual scene in the mind, the eye scans the scene using saccades and then remaps this information (Holmqvist & Andersson, 2017). It is possible to measure saccades in the scene, but this would require algorithms that involve calculating angular velocities and accelerations (Holmqvist & Andersson, 2017) and this is very challenging to accurately measure due to the varying postures, head positions the golfers adopt during their pre-performance routine. Being able to assess visual strategies (both saccades and fixations) and the link to perception action coupling in the environment is going to provide a methodological challenge until mobile eye trackers become more advanced. When possible, future studies could look to address the impact of saccades, by measuring the number of saccades and saccade location pre and post a perceptual-cognitive intervention. Therefore, future research needs to continue to use representative task design to evaluate how the individual is mapping visual information across different environments.

Interestingly when exploring the kinematic factors, club speed decreased post intervention but there were no changes in tempo, forwardswing or backswing. The self-ratings, suggest that the change in club speed, does seem to be a conscious choice as participants were accurately able to evaluate their pace, both pre and post the intervention. No changes in the tempo are consistent with the findings from Study 3b, and the ideal ratio of 2:1 (Grober, 2009). More globally, it is worth noting that the task constrains the way that the individual interacts with the environment, and in this case, the constraints of the putter and putter posture means the tempo is likely to be unaffected by putt type or distance (Grober, 2009; 2011). Taken together with the findings from Study 3b, it could be suggested the differences in task design in Dias *et al.* (2014), namely, the artificial green in a laboratory type setting with a high number of trials impacted on the change in backswing as the participant learnt that they could modify their action this way to meet their task goal. However, participant do not seem to change their backswing to modify motor action when using a representative task design. Future research should continue to explore this interaction and how the golfers can alter their pace in order to putt successfully.

The intervention did not improve the ability to evaluate start line highlighting difficulties in alignment accuracy. This finding suggests perceptual action coupling (Gibson, 1979; Warren, 2006) may be more complex than just having knowledge of the right cues (and this finding cannot be explained through a cognitive approach). The start line errors and ability to evaluate start line errors, are consistent with Study 3b, however, differences between the design in the two studies, enabled the researcher to understand the impact of green reading accuracy on start line. This current study builds on the previous study by highlighting participants are not able to consistently select the correct start line, despite reading the green correctly. These findings also question the importance of start line relative to overall performance. However before any recommendations can be made it is critical to continue to develop further understanding about how perception is linked to action (Land & McLeod, 2000).

The transferability of behaviours (including perception-action and cognitions) is dependent on knowing how to adapt already existing perception-action couplings (Seifert et al., 2016). In support of this, a study with 30 participants (all novice participants) were split into three groups: a control, an auditory guide and visual guide group (Bieńkiewicz et al., 2019). The auditory and visual guide group were given sensory information teaching the novice golfer, how to hit the putt at the ideal ratio, in a ‘copycat’ fashion. The findings revealed performance did improve straight after the intervention, however, the performance improvements were lost when the participants were retested two weeks later as part of a retention test. Research has argued that transferability is the critical feature of expertise (Seifert et al., 2013). Although at this stage, we can’t comment on transferability and expertise gained from the intervention as we did not complete a transfer test so don’t know if the golfers can maintain the performance benefits from the intervention. Understanding the transferability is crucial given that many professional golfers will travel from competition to competition requiring them to adapt to the new conditions quickly. A professional golfer will also travel away for long periods of time so enhancing any retention of performance benefits following an intervention is critical especially if access to coaching is limited. Therefore, we recommend future research employs a design with transfer and retention tests to explore the benefits of a perceptual intervention on performance.

The study also aimed to explore any changes in neural activity based on the perceptual-cognitive intervention. However, due to problems with signal to noise ratio and low trial numbers this analysis could not be completed. This poses an interesting concept as representative task designs do not include high trial numbers, so further research would need to adopt a longitudinal task design. EEG throughout the whole pre-putt routine, including the scanning phrase, would offer methodological challenges but if resolved it would help to provide novel insights into what is changing in the brain and help to provide an understanding of perception-action coupling and resonance mechanisms (Williams et al., 2004).

This study provided a novel insight into how a perceptual-cognitive intervention can be learnt to improve golf putting performance. The intervention improved participants' ability to read the green, hit the desired aim point and select the right cues to evaluate their performance on these variables. Perceptual-cognitive expertise did seem to be sport specific. Changing the task design into a more representative design enabled the researcher to tease out which perceptual variables are important for performance. The perceptual-cognitive intervention did provide enable functional perception-action coupling, however future research is required to check the efficacy of these findings, particular given the methodological limits, such as the small sample size, lack of transfer, retention test and short time between the conditions, meaning that our findings could be indicative of practice effects. Future study ultising a longitudinal design to see if the performance benefits can be maintained, without the need of a guide and to address these limitations. More specifically, it is critical for the development of expertise that the golfer can transfer functional perception-action coupling from one environment to another. Therefore, completing multiple testing sessions to explore transfer is a must prior to concluding this intervention can improve performance. Additionally, as transfer is also influenced by action capacities of the individual and this is known to vary across the expertise spectrum (Seifert et al., 2016b), multiple sessions can help to explore variation over time. Furthermore, longitudinal research is required to help inform how an individual develops expertise over time and how you can adapt the intervention based on the task, situation and action capabilities of the individual.

9.5 Conclusion

The intervention highlighted green reading can be taught and this can improve performance. However, this current study is limited by the technology, the small sample size, the short intervention and the one-off testing session, meaning no retention tasks or transfer tests were completed. These limitations mean the findings in this study are tentative at best. Longitudinal research would address the limitations and enable the researcher to collect clean EEG data and gain further information about how the golfer transfers perceptual information from putt to putt and uses their vision in the here and now to help generate an appropriate motor response. At this stage, tentative understanding of the mechanisms behind the underpinnings of how a participant develops perceptual-cognitive expertise is provided, however, further research is needed especially to explore the complexity of a travelling golfer before any recommendations can be made.

Chapter 10: General Discussion

10.1 Overview

The QE phenomenon has dominated the research into perceptual-cognitive expertise in a range of target-based tasks, such as golf putting and basketball free-throw (Vine & Klostermann, 2017). The popularity of QE is in part, due to the compelling findings QE durations can be used to differentiate between i) both experts and novices and ii) successful and unsuccessful performances in experts (Lebeau et al., 2016). Experts and successful performances are associated with a longer QE duration (Vickers, 2007). It is also believed that a longer QE duration offers a performance advantage over a shorter QE duration (Wilson et al., 2016), and these were the assumptions behind QE intervention training (Vine et al., 2011).

In stark contrast to existing literature, we consistently found shorter QE durations were more effective for performance in comparison to the recommended longer QE duration. Furthermore, we found once practice had been accounted for, a QE intervention which promotes the use of a longer QE duration did not improve performance, using a within participant design. Our findings question the assumptions behind why a longer QE duration is optimal for performance and why you would train a golfer (particularly a highly skilled/elite golfer) in a QE intervention. From an applied perspective, the feasibility of asking a golfer to change their gaze strategy is problematic, with Farrow and Panchuk (2016) advising without a way to explain how QE duration links to performance, it is difficult to explain to an athlete or coach why we should train an athlete to change their gaze behaviour in order to meet ‘optimal’ QE duration times. In the case of QE intervention training, we would go one step further and suggest it is difficult to explain why you would want to ask someone to change from their current practice to something that is more than likely to be less effective for performance. Our findings highlight the potential pitfalls of recommending applied practice, without fully understanding the mechanisms behind any associated increase in performance and without doing due diligence in carrying out multiple training interventions studies with retention and transfer tests (Bishop, 2008; Causer, 2016).

The body of QE research to date has been largely informed by an information-processing perspective towards cognition (Rienhoff et al., 2016), however, particularly in light, of our findings which are not consistent with this perspective, notably, i) a longer QE duration is not required for harder tasks or for performance ii) the same QE duration can lead to both successful and unsuccessful performances and iii) considerable individual differences, we would propose an alternative approach is required. One reason why our findings may not be consistent with findings in current literature is due to our focus on individual trial analysis within our studies. Typically, in current research (and in research that informed optimal QE duration times) QE duration is averaged across trials and participants (Dicks et al., 2017). The problems associated with averaging out QE duration across trials and participants, can be seen in Study 2a. In this study at a group level a QE intervention did improve performance, however, on an individual participant level not everyone improved their performance. In addition, across all studies we found a considerable level of variation within participants and group averages do not account for such differences. Therefore, moving forwards we propose analysis is conducted on an individual level to be able to provide recommendations suitable for individuals (Seifert et al., 2019). Furthermore, when researching from this approach the focus will not be onset and offset, but the notion of 'critical threshold bandwidths'(Davids & Araújo, 2016). In this regard critical thresholds can be established across multiple gaze strategies according to task constraints and individuals, within and between expertise levels (Davids & Araújo, 2016). In this case, functional variability in gaze measures can be predicted based on an individual's ability to 'accept 'invitations for actions' under different task constraints (Davids & Araújo, 2016, p. 3).

We believe these findings also highlight how the focus on the QE duration as the main measure of perceptual-cognitive expertise has limited the scope of perceptual-cognitive expertise research in golf putting. The difficulties in translating research findings into practice may be in part due to fact when researching QE duration, researchers have negotiated the need for other perceptual variables in the environment. For example, golf putting performance is a near and far task, however, the way it has been conceptualised in most studies examining perceptual-cognitive expertise in golf putting is as a near task, as the point of interest has been on the back of the ball only. Critically we found when examining QE durations and other perceptual variables *in situ* we found other perceptual variables in addition to QE duration led to increased performance. For example, in Study 1 (Chapter 4), we found QE duration on the hole followed by a QE duration of the back of the ball was more effective for performance than QE duration on the ball only. In Chapter 5, we also revealed observable differences in the neural activity underlying successful performance with successful putts related to enhanced motor preparation. Our findings are consistent with other research that has found experts have advanced motor preparation (Del Percio et al., 2009; Hung et al., 2004). More specifically, we found for successful putts there was an observable BP, whereas for misses there was not. Additionally, successful putts had a greater BP peak negativity and this is consistent with Mann *et al.* (2011) who found low handicap golfers (expert) had a greater BP peak amplitude in comparison to higher handicap golfers (less-expert). It has been postulated that neural activity at BP peak is linked to visuomotor control (Coombes et al. 2010). Accordingly, Mann *et al*. (2011) concluded the expert golfers had enhanced preparation and allocated more attention to the visuomotor components of putting in comparison to the less-experts.

In our cohort of highly skilled golfers, we found differences in gaze behaviours related to performance during the pre-preparation routine with an increase of saccades back and forth from the hole prior to the initiation of the motor action (taking the putter back) for unsuccessful putts in comparison to successful putts. We also found significantly more eye movements for unsuccessful putts in comparison to successful putts during the last second prior to contact and that eye movements were present for unsuccessful putts during the time window of the BP peak for the successful putts. Research into visusomotor control has indicated that there is a link between visual input and the final motor output (Goodale, 2011). Thus suggesting the reduction of eye movements could potentially allow for more enhanced preparation as there was a clearer strategy in regards where to look prior to the action. In the unsuccessful putts eye movements maybe related to indecision and differences in visual input or visual input processing. Our findings demonstrate the merit of exploring expertise based differences within highly skilled athletes. We suggest future research continues to explore within expertise differences to create evidence-based recommendations.

We also found a greater decrease in beta power, which was maximal at the time point -2000ms to -1000ms preceding contact for the successful putts in comparison in missed putts in the central-parietal region over the motor cortex (C3, Cz, C4, CP1, CP2). There was a similar pattern for in SMR with a significant performance and time interaction, however, post hoc testing was not significant. Suppression is believed to be indicative of the activation of the sensorimotor networks (Pfurtscheller & Lopes da Silva, 1999), thus suggesting earlier suppression led to enhanced movement planning

(Pfurtscheller et al., 2006). In support of our findings, Cooke *et al.* (2014) found a greater decrease in beta power for experts in comparison to novices in the final seconds preceding the putt. Likewise, Del Percio *et al*. (2009) found expert shooters have enhanced preparation as characteristed by a greater decrease in beta amplitude. Cooke *et al*. (2014) speculated a greater decrease in beta was indicative of experts devoting more neural resources to the response programming of golf putts to actively inform the programming of movement direction and force (cf. Neubauer & Fink, 2009; Pfurtscheller, 1992). Our findings extend findings beyond the expert- novice paradigm and suggest within highly skilled golfers' superior performance is related to earlier preparation.

Findings also revealed there were changes in task specific process (Pfurtscheller, 2001) with an increase in relative power (%) from baseline in Fmθ at Fz at -1000ms to -500ms, reflective of increased attention during the aiming period and a known characteristic of expert performers (Baumeister et al., 2008; Doppelmayr et al., 2008; Loze et al., 2001). In contrast, research with eighteen skilled golfers found Fmθ power significantly decreased for the best putts compared with the worst putts (Kao et al., 2015). The authors concluded higher Fmθ power was detrimental to performance as resulted in excessive attentional control, whereas lower Fmθ power enabled optimal attention. The detrimental effect of 'reinvesting' conscious control i.e., devoting attentional resources to the action/movement during proceduralised actions is well established (Masters, 1992). Research has found individuals who show a greater tendency toward conscious monitoring are more likely to underperform in golf putting, particularly when using a repetitive putt set up (Maxwell et al., 2006). Future research is required to understand the nature of relationship between Fmθ and performance, particularly as manipulation of Fmθ using neurofeedback has been proposed to improve sporting performance (Kao et al., 2015).

An increase in relative power (%) from baseline in alpha was found at the electrode C4 at the time window -1000ms to -500ms for successful putts in comparison to missed putts. Changes in relative alpha power at C4 has been linked to enhanced fine motor control (Cheron et al., 2016), suggesting functional inhibition of the left hand/arm (Klimesch et al., 2007) for successful putts. The left arm/hand in golf putting is thought to influence the direction of the putter face and help to keep the putter square at contact (Pelz, 2000). In contrast to our findings Babiloni *et al.* (2008) found a decrease in alpha power at C4 in elite golfers using a modified golf putting task and concluded the left arm/hand movements was related to superior success. In addition, to the modification in hole sizes used in Babiloni *et al*. (2008) study, there was also differences in the baselines used (-5 to -4 seconds in contrast to 3-2.5 seconds in our study). These methodological differences could influence the change relative to baseline and the task processing required. From an applied perspective understanding whether it is inhibition is important as inhibition can limit and control excitatory processes (Pfurtscheller & Lopes da Silva, 1999). We recommend future research using a representative task design to explore the directional relationship of alpha power at C4 relative to performance.

Furthermore, a relative decrease in alpha power in central regions has also been related to expertise in golf putting (Cooke et al., 2014; Gallicchio et al., 2017). More specifically, Gallicchio *et al*. (2017) found the inhibition of irrelevant cortical regions was crucial for performance. A decrease in relative alpha power at C3 is consistent with the neural efficiency hypothesis reflecting a reduction of cognitive processing and high level of automaticity (Del Percio et al., 2009; Fitts & Posner, 1967). Based on the neural efficiency hypothesis (Del Percio et al., 2009) it would also be expected to see desynchronization of alpha (Pfurtscheller, 2014), rather than increase in alpha power. However, it could be argued our alpha findings are indicative of proficiency i.e., maintaining successful performance through switching effectively between an automated and a more controlled execution according to the task and situational demands (Bertollo et al., 2016). Traditionally the neural efficiency has focused on expert vs novice differences and in our study, we focused on differences within a highly skilled cohort. Differences within experts may be due to individual differences in performance states on the day (Bertollo et al., 2016). Observations of the data at an individual level highlighted the potential need to profile each athlete (with both relative increases and decreases in alpha found). Critically, before any recommendations can be made, future study ultising longitudinal designs is required to further explore the concepts of inhibition and neural efficiency. These studies are critical to progress the knowledge underpinning expert performance (Park et al., 2015) and to ensure accurate guidance is disseminated to coaches, practitioners and athletes.

Ambiguity in the relationship between QE duration and performance prompted us to look beyond QE duration and consider other perceptual-cognitive aspects that could link to performance in golf putting. Our findings revealed that a golfer's ability to attend to perceptual information in the environment prior to putting is directly linked to putting performance. However, critically expertise-based differences could only be found using a representative task *in situ*, not when using a 2D based screen task. The 2D screen task using in Study 3a is indicative of a task used from a cognitive approach. The cognitive approach explores perceptual expertise by measuring indirect perception (Araújo et al., 2017). From this theoretical perspective the 'input'/processing information sources (presented by asking participants to view snapshots of performance environments derived from still 2D images short video clips) is viewed as the critical component and the actual action task is not important (Renshaw et al., 2019), often with participations responding through the use of a key press (Araújo et al., 2017). Whereas study 3b and 4, these studies were designed using a representative task whereby the perceptual variables pre-action and the action response in research were matched to the task demands of applied competitive golf. In these studies, we wanted to explore perception in action, so the action response was designed to hit a putt (including gaining perceptual information post putt on the action). These studies provide support for the need to consider the choice of action response when designing research studies to inform practice (Renshaw et al., 2019). In support of our findings, it has been found an indirect image of a ball in flight simulated on a 2-dimensional video screen is not appropriate to train crickets. Subsequently, the researchers advocate the need to use an Ecological Dynamics approach and match the specific action in order to measure perception action coupling (Pinder et al., 2011; Stone et al., 2014).

In Chapter 9, we also found tentative evidence to support the performance merits of a perceptual intervention, especially owing to the improvements in success rate at the first putt for each distance post intervention in comparison to pre. There were limitations with the study design so we acknowledge the performance changes could equally be attributed to practice time alone. However, it is important to discuss the premise of the intervention, why the intervention may work and what the implications are the wider development of perceptual expertise in putting. The intervention was designed to give direct "knowledge of" the environment (see Araújo et al., 2009; Araújo & Davids, 2011) to support how an individual interacts with a performance environment, intentionally, enabling the participant to utilise affordances from the performance environment (defined as *opportunities for action,* Gibson 1956). However, it must be noted, the perceptual intervention, guided the golfer towards the relevant perceptual variables in the environment and further research is needed to understand how participants can find, select and use perceptual information from the environment without the use of the guide. It is proposed that future work on developing understanding of how participants can select and find perceptual information (affordances) in the environment should use eye tracking data, specifically examining saccades and fixations during the pre-performance routine when scanning the green and post putt as part of monitoring and evaluating their putt. The limits of eye trackers will restrict the scope of view to central vision and does not pick up all the information in the visual field (Holmqvist & Andersson, 2017), however there is the need to focus on more visual strategies beyond QE duration. Critically, we recommend future research focuses on how vision is being used throughout the whole putt routine, such as but not limited to, fixations when scanning the green and fixations when looking at the ball and hole together, rather than just on QE duration alone, in accordance with an Ecological Dynamics approach.

Following the intervention, not only did performance improve but participants improved their accuracy to evaluate such perceptual variables as green reading, pace, and ability to hit the intended aim point. In contrast QE viewing time on the back of ball prior to QE and, QE duration did not change between the control condition and intervention condition, suggesting that the intervention did not directly influence these measures and the need for future research exploring perceptual-cognitive expertise to consider vision beyond QE duration. It could therefore be suggested, the inherent lack of representative design within traditional QE studies may have unintentionally limited the ability to transfer the findings into an applied domain as traditional QE study designs do not take into consideration other information within the perceptual field (Renshaw et al., 2019). Taken together our findings reinforcing how complex understanding perception action in practice is and the need to gain understanding on the continuous interactions in the environment and the role task constraints prior to being able to able to differentiate markers of perceptual expertise (Araújo et al., 2017). An Ecological Dynamics approach will allow the researcher to explore the continuous interactions in the environment and therefore exploring perceptual expertise in golf putting.

In this thesis, when exploring the interaction between the athlete, task and environment, a consistent feature across all the studies is that even highly skilled/elite (Tour Professionals or + handicap) golfers, vary in their behaviour (eye tracking, neural activity and performance). Similar accounts of individual differences between experts has been reported in literature (Abernethy, 1991; Bootsma, 1989, Farrow et al., 2018, Williams & Ericsson, 2005). Understanding this variation is important as Ericsson (2003) has commented, understanding such differences reveals important alterations in the way successful sporting performances can be achieved. Therefore, we recommend future studies look to explore this variation in more detail.

Critically, our findings identified that a golfer's interactions with the environment and the associated dynamic process of perception action coupling is depend on the context of the testing environment, consistent with research in other sports (Stone et al., 2014; Stone et al., 2017). Understanding and acknowledging differences in behaviour based on task design and associated perceptual variables present in the testing environment is important to allow the effective transfer of knowledge to the applied sport domain (Roca & Williams, 2016). Notably, we found performance scores were only comparable to the applied competitive setting when using a representative task design and QE duration was lower in a representative task design in comparison to a non-representative task design. These differences may be due to differences inherent in the task and environment. For example, in a representative task design, participants complete their full routine (up to 40 seconds in length); including, having an opportunity to search for perceptual information in the environment by scanning the green before each putt. In a representative task design, participants will complete putts from different locations which vary in type, meaning the participant will need to account for these changes, to be successful throughout the testing session. In comparison when a participant completes a task design which is less representative, that involves a high number of repetitive putts with putts taken from one location, typically, pre-performance routines are much shorter. The shorten duration could be linked to the fact that participants do not move their feet in between putts and engaging in less scanning of the green as they do not need to account for changes in the environment. By comparing findings from less representative task design to more representative task design throughout this thesis, has identified the importance of matching the surrounding environment when measuring perceptual cognitive skill within golf putting.

Moving from the laboratory and screen-based designs has enabled a fundamental change in which elements of the putting routine can be measured allowing the task design to be matched to the competitive environment. Matching the task increases functionality and fidelity of the research (*cf.* Pinder et al., 2011) as there is consistency in the action, time taken to complete the putt routine and perceptual variables in the environment. Expanding the research focus to the whole putting routine, including pre-motor action, where the golfer is scanning the green and immediately after the motor action, has revealed how multi-faceted perceptual-cognitive expertise in golf putting is. Therefore, based on our findings, to enable accurate dissemination, it is recommended that future testing exploring perceptual-cognitive expertise in golf putting is conducted i) using a representative task design; ii) measures the whole putting action; and iii) is underpinned by an ecological approach to explore the interaction between the athlete, task and environment (Araújo & Davids, 2009). Closing the gap between research and practice is paramount, particularly focusing on how perceptual-cognitive expertise is developed and related to golf putting success and continuing to measure behaviour in context to assess how the golf player addresses, and copes with, the unpredictability of the environment whilst still being able to successfully perform (Araújo et al., 2007).

10.2 Strength and Limitations

There are challenges associated with measuring perceptual-cognitive expertise in golf putting. Using a variety of methods has enabled us to develop greater understanding towards the markers of perceptual expertise in golf putting. For example, the temporal resolution of mobile EEG enabled us to identify neural signatures characterising successful and unsuccessful putts. At this stage, the challenge lies in collecting brain activity using a representative task design, ideally outdoors. When using a representative task design, it was not possible to collect clean EEG data because not enough trials were retained after processing to enable a comparison between pre and post intervention in one session. To address this limitation, future study, should take a longitudinal approach to capturing EEG data with an individual over multiple sessions to understand individual differences and capture enough clean trials. Currently, inconsistencies in methodologies across studies which have captured EEG data has restricted the researcher’s ability to make any firm conclusions. It is proposed that in future studies, a standardised approach i.e., using the same epoch, baseline, filtering and ICA analysis and trigger/timestamping would enable greater understanding of the signal to trial ratio required to confidently differentiate between signal (neural activity) and noise (Bénar et al., 2007). Furthermore, there was problems with eye movements within the EEG, particularly when exploring MRCPs and future research should look to add additional electrodes to try and limit the potential for head movement artifacts. Additionally, in the future, the aim would be to synchronise the EEG and eye tracker technology, so they can be analysed in combination and saccades and fixations can be used to time stamp the EEG. The synchronisation of data would enable us to gain further understanding of how gaze activity when scanning the green pre and post motor action is related to current performance and future learning. It is hoped future advancements in technology will allow the eye tracker to be used in variable light conditions (Moran, Campbell, & Ranieri, 2018) to fulfil the aim of collecting data on an outdoor green.

Limitations, (such as the small sample size, lack of transfer, retention test and short time between the conditions) in the design of the final study does limit the ability to disseminate applied findings and the potential efficacy of the intervention. Future study ultising a longitudinal design is required to explore if performance benefits can be maintained and check that they are not due to practice effects. Given the nature of expertise required within a highly skilled (travelling) golfer, completing multiple testing to explore transfer is a must prior to concluding this intervention works to improve performance.

10.3 Concluding remarks

In conclusion, this thesis has demonstrated how visual gaze and neural processes can be used to help inform golf putting performance. The inherent variation in eye tracking behaviour and lack of reliability of QE duration when tested over multiple testing sessions means that generic group recommendations on eye tracking behaviours are not appropriate. Furthermore, the overarching aim of this thesis was to capture applied sporting behaviour within the testing environment. Taking this approach has provided fruitful insights demonstrating the importance of researching and acknowledging the role perceptual-cognitive expertise has in putting performance..

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Appendix 1

Study 1- Additional Error Analysis

1.1 Error as a function of skill level

As can be seen in Figure 69 and Table 19, for 8ft putts there was no difference in error location between the two groups ($F_{(1,2040)} = 2.31$, $p = 0.128$). In contrast, at 15ft there was a statistically reliable difference in error location between the two groups ($F_{(1,2284)} = 8.63$, $p = 0.04$). For 25ft there was also a significant difference in the error location ($F_{(1,2646)} = 69.02$, $p < 0.001$) between the two groups. Taken together these results suggest at the longer putt distance, high skilled golfers error location varies less in comparison to lower skilled golfers.

Table 19. Differences in error location as a function of skill level.

	Putt Distance (ft)	*Mean Resultant Vector (°)*	*R Length (0,1)*	*Raleigh Test of Uniformity (p = < 0.05)*
	8	181	0.57	<0.001
Lower Skill	15	160.46	0.18	<0.01
	25	172.79	0.16	<0.02
	8	180.72	0.64	< 0.001
Higher Skill	15	177.87	0.41	<0.001
	25	128.79	0.22	<0.001

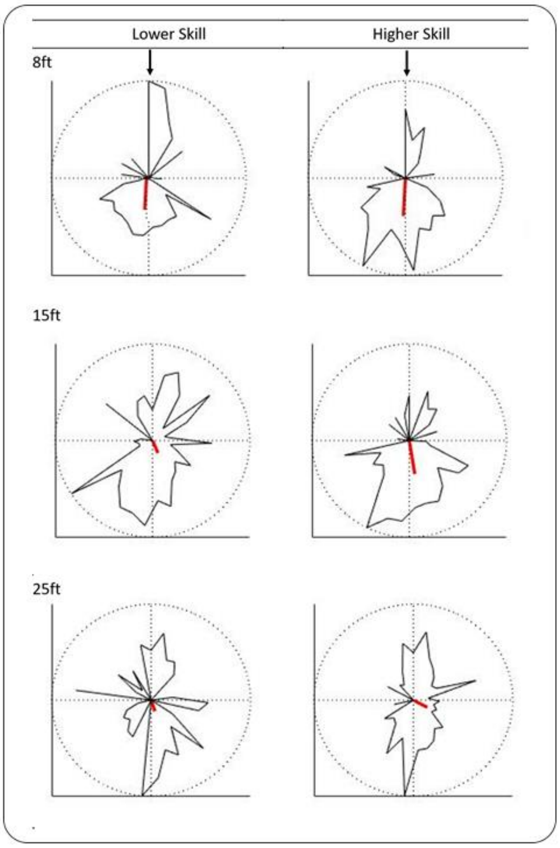


Figure 69. The distribution of errors from missed putts. The black arrow indicates the direction of the ball from the putter. Each plot is normalised to a 0-1 scale (with the centre of the graph representing the hole, and the outer ring representing the largest mean error for that data set). Each plot represents the distribution of missed putts around the hole, shown separately as a function of putt distance (8ft, 15ft, 25ft) and skill level (lower/higher median split based on average putts per round). The black line represents the mean distribution of errors around the hole, calculated in successive 10 degree bins (averaged across all misses within each bin). The red vector illustrates the overall mean direction of errors (expressed as an angle in degrees relative to the original direction of the putt, in a clockwise direction), with the length of the line reflecting the circular spread of the error distribution (the R Length; the closer it is to one, the more concentrated the data sample is around the mean direction).

1.2 Error as a function of QE duration

As can be seen in Figure 70 and Table 20, for 8ft putts there was a significant difference in the distribution of errors between the two groups ($F_{(1,2323)} = 1.63$, $p = 0.02$) with higher QE duration resulting in less variation of error. For 15ft, there was a reliable statistical difference in error location (mean angle direction) between the two groups ($F(1,2370) = 3.75$, $p = 0.03$), with higher QE duration leading to less variability in error. In contrast, at 25ft, there was not a reliable difference in error location ($F_{(1,2952)} = 41.13$, $p = 0.201$).

Table 20. Differences in error location as a function of QE duration.

	Putt Distance (ft)	*Mean Resultant Vector (°)*	*R Length (0,1)*	*Raleigh Test of Uniformity (p = < 0.05)*
Lower QE	8	179.62	0.20	<0.001
	15	147.13	0.21	<0.01
	25	178.47	0.11	<0.01
Higher QE	8	174.15	0.39	< 0.001
	15	168.39	0.19	<0.001
	25	181.34	0.12	<0.001

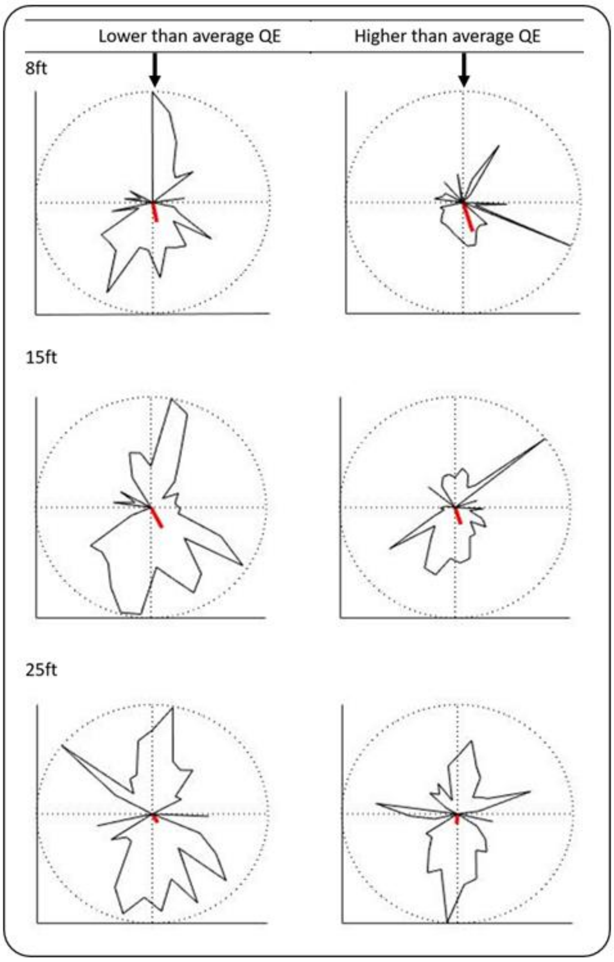


Figure 70. The distribution of errors from missed putts. The arrow indicates the original direction of the putter. Each plot is normalised to a 0-1 scale (with the centre of the graph representing the hole, and the outer ring representing the largest mean error for that data set). Each plot represents the distribution of missed putts around the hole, shown separately as a function of putt distance (8ft, 15ft, 25ft) and QE duration (lower/higher median split based on average QE duration). The black line represents the mean distribution errors around the hole, calculated in successive 10 degree bins (averaged across all misses within each bin). The red vector illustrates the overall mean direction of errors (expressed as an angle in degrees relative to the original direction of the putt, in a clockwise direction), with the length of the line reflecting the uniformity of the error distribution (the R value; increasing values reflect greater uniformity).

Study 2a

1.3 Error as a function of QE intervention

As shown in Figure 71, the mean direction from the hole for golfers between the control and QE intervention were similar (179.62° and 182.15° respectively), accompanied by a difference in the mean R Length (0.67 and higher 0.70). In both groups, the error location indicated a significant departure from uniformity ($p < 0.001$ and $p < 0.001$) however, there was no significant difference in the distribution of errors between the two groups ($F_{(1,566)} = 13.79$, $p = 0.567$), meaning error location did not change as a function of QE intervention.

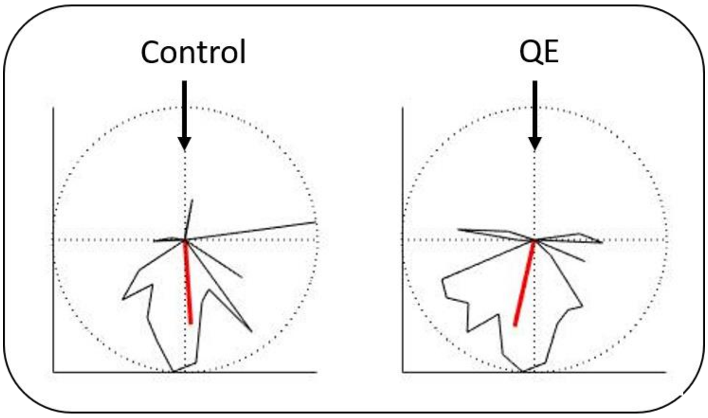


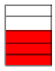
Figure 71. The distribution of errors from missed putts. The black arrow indicates the direction of the ball from the putter. Each plot is normalised to a 0-1 scale (with the centre of the graph representing the hole, and the outer ring representing the largest mean error for that data set). Each plot represents the distribution of missed putts around the hole, shown separately as a function of QE intervention. The black line represents the mean distribution of errors around the hole, calculated in successive 10-degree bins (averaged across all misses within each bin). The red vector illustrates the overall mean direction of errors (expressed as an angle in degrees relative to the original direction of the putt, in a clockwise direction), with the length of the line reflecting the circular spread of the error distribution (the R Length; the closer it is to one, the more concentrated the data sample is around the mean direction).

Appendix 2
Example Questions from Screen-based task

https://stirlingpsych.eu.qualtrics.com/jfe/form/SV_4T9NkS3fn79zOoB

Selected extract of questions are presented below:

How would you rate your green reading ability? (1 coloured bar is not very skilled and 5 coloured bars is highly skilled). To rate slide the green circle button up and down.



How often do you spend time reading the green before you putt?

	Not at all	Often	Every Putt
Practice	○	○	○
Competitive Round	○	○	○

What type of activities do you do; or have you done in the past, to improve your green reading skills?

What device are you using to fill out this survey?

- ○ Smart Phone
- ○ Tablet
- ○ Laptop
- ○ Desktop Computer

What read do you think this putt is?

- ○ Straight and Level
- ○ Straight Uphill
- ○ Straight Downhill
- ○ L-R Level
- ○ L-R Uphill
- ○ L-R Downhill
- ○ R-L Level
- ○ R-L Uphill
- ○ R-L Downhill

If you were to hit this putt (same putt as the previous question), what would be the pace of your intended putt? To select the pace slide the green button across the bar.

Falling into the hole on the last roll (aka dying into the hole) — Hitting the back of the hole at pace

0 — 1

How confident are you in your read?

Looking at the same putt, which side would you be aiming to land the putt, if it did not land in the hole? To select your side, please click on one of the boxes in the picture below.

Looking at the same putt, select the views you wish to use to read this putt and that you would use to read if this was an on course putt. Press the green next button to view the positions you have chosen.

- ☐ Back of the hole
- ☐ Front of the hole
- ☐ Left side
- ☐ Right Side
- ☐ Crouched down front of the hole
- ☐ Crouched down back of the hole

Back of the hole

These page timer metrics will not be displayed to the recipient.
First Click: *0 seconds*
Last Click: *0 seconds*
Page Submit: *0 seconds*
Click Count: *0 clicks*

Crouched back

These page timer metrics will not be displayed to the recipient.
First Click: *0 seconds*
Last Click: *0 seconds*
Page Submit: *0 seconds*
Click Count: *0 clicks*

Thinking of the viewing positions, please rate how useful the information was in the photo of the viewing position to help you to make your decision on the read of the putt.

	Very Useful	Useful	Somewhat Useful	Not Useful	N/A (Did not view the position)
Front of Hole	○	○	○	○	○
Back of Hole	○	○	○	○	○
Left Side of the Hole	○	○	○	○	○
Right Side of the Hole	○	○	○	○	○
Front crouched	○	○	○	○	○
Back crouched	○	○	○	○	○

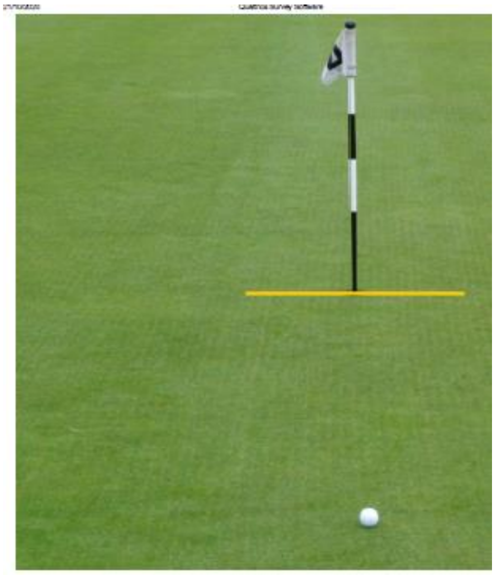

Front of the hole


Crouched front


Left Side


Right Side

Looking at the same putt, please click on the yellow line (on the picture going across the hole), to mark your intended aim point.



The golfer in this photo, has read the green and then marked the intended path that they wish the ball to take by using the blue markers. In the question below (and subsequent other questions) asking you to mark your intended path through clicking on the picture, please use this photo as a guide and click on the picture as you were using the blue markers.

Please click on the picture to mark the path you intend the putt to take.

Looking at the same putt, please click on the sources you used in the environment to make your decision.

If No, what is your new read of the putt?

If you were to hit this putt, what would be the pace of your intended putt?

Falling into the hole on the last roll (aka dying into the hole)	Hitting the back of the h at pace
0	1

How confident are you in your new read?

Please click on the yellow line to mark the new intended aim point.

Please describe below, any other sources of information that you would normally use to help you to make your decision that are not present in the picture.

After considering the putt further do you still agree with your read from before?

Yes	No
○	○

Please click on the picture to mark the new path you intend the putt to take.

Watch this video of the putt. Do you still agree with your read of the putt?

○ Yes
○ No

If no, what do you think the read is now?

What information in the video influenced your decision to change your read of the putt?

Is the ball going to:

○ Go into the hole
○ Miss the hole

Using the read information above, please watch the video and think about if the ball is going to go into the hole or miss the hole.

Watch the video and describe the read and pace of the putt.

If you had to hit the same putt, how confident would you be in your read after watching this video?

Appendix 3

Study 4- Golf and Coach Rating: Pre and Post the Intervention

Chi square analysis comparing the golfers' and coach's rating pre (white fill) and post the intervention (grey fill) on green reading accuracy, start line, pace, aim point and execution (Chapter 9)

Table 21. Significant differences in judging green reading accuracy between the golfer and the coach based on Chi Square analysis.

Putt Type		Golfer		Coach		*DF*	*Chi Square*	*Sig*	
		Accurate	*Inaccurate*	*Accurate*	*Inaccurate*				
Pre-Intervention	Putt 1, Trial 1	6	3	0	9	1	9.00	0.03	Yes
Pre-Intervention	Putt 1, Trial 8	8	1	4	5	1	4.00	0.046	Yes
Pre-Intervention	Putt 1, Trial 9	8	1	4	5	1	4.00	0.046	Yes
Pre-Intervention	Putt 1, Trial 10	9	0	4	5	1	6.923	0.009	Yes
Pre-Intervention	Putt 2, Trial 7	9	0	6	3	1	3.600	0.05	Yes
Pre-Intervention	Putt 3, Trial 1	3	6	0	9	1	3.600	0.05	Yes
Pre-Intervention	Putt 3, Trial 9	3	6	0	9	1	3.600	0.05	Yes
Pre-Intervention	Putt 4, Trial 1	4	5	0	9	1	6.923	0.009	Yes
Pre-Intervention	Putt 4, Trial 5	9	0	6	3	1	3.600	0.05	Yes
Pre-Intervention	Putt 4, Trial 6	9	0	6	3	1	3.600	0.05	Yes
Pre-Intervention	Putt 4, Trial 7	8	1	4	5	1	4.00	0.046	Yes
Pre-Intervention	Putt 4, Trial 8	8	1	3	6	1	5.844	0.016	Yes
Pre-Intervention	Putt 4, Trial 9	8	1	4	5	1	4.00	0.046	Yes
Pre-Intervention	Putt 4, Trial 10	9	0	4	5	1	6.923	0.009	Yes
Post-Intervention	Putt 2, Trial 1	9	0	4	5	1	6.923	0.009	Yes

Table 22. Significant differences in judging start line accuracy between the golfer and the coach based on Chi Square analysis.

Putt Type		Golfer		Coach		*DF*	*Chi Square*	*Sig*	
		Accurate	*Inaccurate*	*Accurate*	*Inaccurate*				
Pre-Intervention	Putt 1, Trial 1	7	2	3	6	1	3.600	0.05	Yes
Pre-Intervention	Putt 1, Trial 4	7	2	2	7	1	5.556	0.018	Yes
Pre-Intervention	Putt 1, Trial 5	9	0	2	7	1	11.445	0.001	Yes
Pre-Intervention	Putt 1, Trial 6	9	0	0	9	1	18.00	<0.001	Yes
Pre-Intervention	Putt 1, Trial 8	8	1	1	8	1	10.889	0.001	Yes
Pre-Intervention	Putt 1, Trial 9	8	1	2	7	1	8.100	0.004	Yes
Pre-Intervention	Putt 1, Trial 10	9	0	2	7	1	11.445	0.001	Yes
Pre-Intervention	Putt 2, Trial 3	8	1	4	5	1	4.00	0.046	Yes
Pre-Intervention	Putt 2, Trial 5	6	3	2	7	1	3.600	0.05	Yes
Pre-Intervention	Putt 2, Trial 7	9	0	5	4	1	5.143	0.023	Yes

Pre-Intervention	Putt 3, Trial 1	8	1	4	5	1	4.00	0.046	Yes
Pre-Intervention	Putt 3, Trial 2	6	3	2	7	1	3.600	0.05	Yes
Pre-Intervention	Putt 3, Trial 4	9	0	3	6	1	9.00	0.003	Yes
Pre-Intervention	Putt 3, Trial 5	8	1	4	5	1	4.00	0.046	Yes
Pre-Intervention	Putt 3, Trial 7	9	0	5	4	1	5.143	0.023	Yes
Pre-Intervention	Putt 3, Trial 9	8	1	3	6	1	5.844	0.016	Yes
Pre-Intervention	Putt 3, Trial 10	9	0	4	5	1	6.923	0.009	Yes
Pre-Intervention	Putt 4, Trial 2	9	0	5	4	1	5.143	0.023	Yes
Pre-Intervention	Putt 4, Trial 3	8	1	1	8	1	10.889	0.001	Yes
Pre-Intervention	Putt 4, Trial 5	8	1	1	8	1	10.889	0.001	Yes
Pre-Intervention	Putt 4, Trial 6	7	2	2	7	1	5.556	0.018	Yes
Pre-Intervention	Putt 4, Trial 7	9	0	3	6	1	9.00	0.003	Yes
Pre-Intervention	Putt 4, Trial 8	9	0	3	6	1	9.00	0.003	Yes
Pre-Intervention	Putt 4, Trial 9	9	0	4	5	1	6.923	0.009	Yes
Post-Intervention	Putt 1, Trial 2	9	0	3	6	1	9.00	0.003	Yes
Post-Intervention	Putt 1, Trial 3	8	1	3	6	1	5.844	0.016	Yes
Post-Intervention	Putt 1, Trial 4	8	1	3	6	1	5.844	0.016	Yes
Post-Intervention	Putt 1, Trial 10	8	1	2	7	1	8.100	0.004	Yes
Post-Intervention	Putt 2, Trial 1	9	0	3	6	1	9.00	0.003	Yes
Post-Intervention	Putt 2, Trial 7	9	0	4	5	1	6.923	0.009	Yes
Post-Intervention	Putt 2, Trial 9	8	1	2	7	1	8.100	0.004	Yes
Post-Intervention	Putt 2, Trial 10	9	0	5	4	1	5.143	0.023	Yes
Post-Intervention	Putt 3, Trial 4	8	1	3	6	1	5.844	0.016	Yes
Post-Intervention	Putt 3, Trial 5	8	1	4	5	1	4.00	0.046	Yes
Post-Intervention	Putt 3, Trial 6	8	1	4	5	1	4.00	0.046	Yes
Post-Intervention	Putt 4, Trial 8	8	1	4	5	1	4.00	0.046	Yes
Post-Intervention	Putt 4, Trial 10	8	1	4	5	1	4.00	0.046	Yes

Table 23. Significant differences in judging pace accuracy between the golfer and the coach based on Chi Square analysis.

Putt Type		Golfer		Coach		*DF*	*Chi Square*	*Sig*	
		Accurate	*Inaccurate*	*Accurate*	*Inaccurate*				
Pre-Intervention	Putt 1, Trial 2	8	1	4	5	1	4.00	0.046	Yes
Pre-Intervention	Putt 4, Trial 1	5	4	9	0	1	5.143	0.023	Yes
Post-Intervention	Putt 1, Trial 3	8	1	4	5	1	4.00	0.046	Yes
Post-Intervention	Putt 2, Trial 2	8	1	4	5	1	4.00	0.046	Yes
Post-Intervention	Putt 2, Trial 8	9	0	5	4	1	5.143	0.023	Yes

Table 24. Significant differences in judging aim point accuracy between the golfer and the coach based on Chi Square analysis.

Putt Type		Golfer		Coach		*DF*	*Chi Square*	*Sig*	
		Accurate	*Inaccurate*	*Accurate*	*Inaccurate*				
Pre-Intervention	Putt 2, Trial 3	6	3	1	8	1	5.844	0.016	Yes
Pre-Intervention	Putt 2, Trial 6	7	2	2	7	1	5.556	0.018	Yes
Pre-Intervention	Putt 2, Trial 7	9	0	4	5	1	6.923	0.009	Yes
Pre-Intervention	Putt 4, Trial 5	8	1	3	6	1	5.844	0.016	Yes
Pre-Intervention	Putt 4, Trial 6	8	1	4	5	1	4.00	0.046	Yes
Pre-Intervention	Putt 4, Trial 7	9	0	3	6	1	9.00	0.003	Yes
Pre-Intervention	Putt 4, Trial 8	9	0	2	7	1	11.445	0.001	Yes
Pre-Intervention	Putt 4, Trial 9	9	0	5	4	1	5.143	0.023	Yes
Post-Intervention	Putt 1, Trial 4	8	1	4	5	1	4.00	0.046	Yes
Post-Intervention	Putt 2, Trial 3	9	0	5	4	1	5.143	0.023	Yes
Post-Intervention	Putt 2, Trial 9	8	1	4	5	1	4.00	0.046	Yes
Post-Intervention	Putt 3, Trial 3	9	0	5	4	1	5.143	0.023	Yes
Post-Intervention	Putt 3, Trial 9	8	1	4	5	1	4.00	0.046	Yes
Post-Intervention	Putt 4, Trial 9	8	1	3	6	1	5.844	0.016	Yes

Table 25. Significant differences in judging execution accuracy between the golfer and the coach based on Chi Square analysis.

Putt Type		Golfer		Coach		*DF*	*Chi Square*	*Sig*	
		Accurate	*Inaccurate*	*Accurate*	*Inaccurate*				
Pre-Intervention	Putt 1, Trial 3	3	6	8	1	1	5.844	0.016	Yes
Pre-Intervention	Putt 1, Trial 6	9	0	5	4	1	5.143	0.023	Yes
Pre-Intervention	Putt 2, Trial 3	3	6	9	0	1	9.00	0.003	Yes
Pre-Intervention	Putt 2, Trial 3	4	5	9	0	1	6.923	0.009	Yes
Pre-Intervention	Putt 2, Trial 8	5	4	9	0	1	5.143	0.023	Yes
Pre-Intervention	Putt 3, Trial 1	6	3	9	0	1	3.600	0.05	Yes
Pre-Intervention	Putt 3, Trial 4	9	0	6	3	1	3.600	0.05	Yes
Pre-Intervention	Putt 3, Trial 6	8	1	4	5	1	4.00	0.046	Yes
Post-Intervention	Putt 1, Trial 10	8	1	4	5	1	4.00	0.046	Yes
Post-Intervention	Putt 2, Trial 9	8	1	3	6	1	5.844	0.016	Yes